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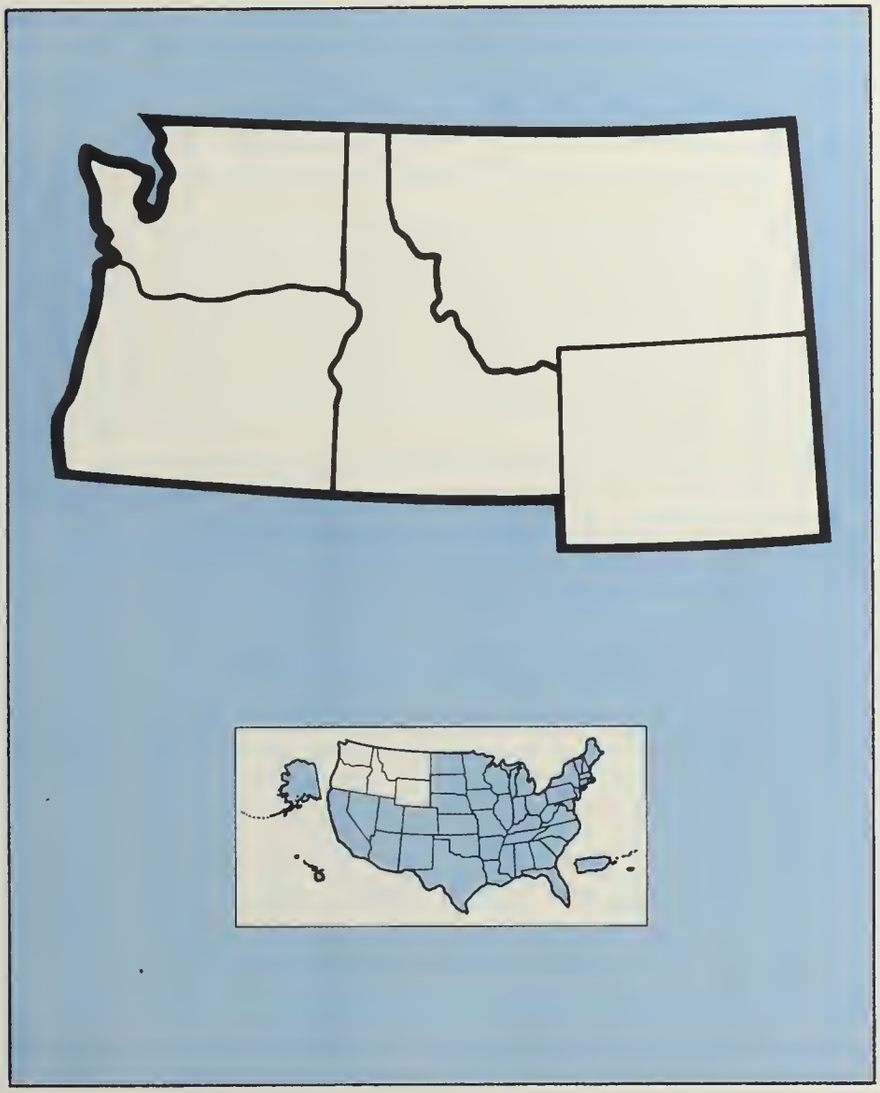

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WIND ENERGY RESOURCE ATLAS:
Volume 1 - The Northwest Region

D. L. Elliott
W. R. Barchet

April 1980

Prepared for
the U.S. Department of Energy
Under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

PREFACE

For the purpose of assessing the national wind resource, the United States and its possessions have been divided into twelve regions. For each region, wind resource assessments are presented in the form of an atlas. The atlases depict in graphic, tabular and narrative form the wind resource on a regional and state level. The information presented in the atlases will help guide homeowners, utilities and industry in decisions concerning the use of the wind as a source of energy.

This atlas of the wind energy resource is composed of introductory and background information, a regional summary of the wind resource, and assessments of the wind resource in each state of the region. Chapter 1 provides background on how the wind resource is assessed and on how the results of the assessment should be interpreted. A description of the wind resource on a regional scale is then given in Chapter 2. The results of the wind energy assessments for each state are assembled in this chapter into an overview and summary of the various features of the regional wind energy resource. Chapter 3 provides an introduction and outline to the descriptions of the wind resource given for each state. Assessments for individual states are presented as separate chapters beginning with Chapter 4. The state wind energy resources are described in greater detail than is the regional wind energy resource, and features of selected stations are discussed. This preface outlines the use and interpretation of the information found in the state chapters.

Much of the information in the state chapters is given in graphic or tabular form. As is discussed in Section 3.1, the sequence of maps, tables, and graphs is the same in each state chapter. References to these figures and tables are made here with an asterisk (*) in place of the chapter number (e.g., Figure *.1, Table *.2). Similar maps and tables are found in Chapter 2 on the regional wind resource. References to the regional maps and tables are made in brackets, [ ].

Figure *.1 shows the major geographical (mountains, rivers) and cultural (cities, towns) features in the state [Figure 2.1]. This map can be used to orient the reader to the state. Figure *.2 portrays the topography of the state in shaded relief [Figure 2.2]. The shaded relief allows the reader to visualize the character of the terrain surrounding locations of special interest. Superimposed on these state maps (but not the regional maps) is a grid of dashed lines one-third degree (20') longitude by one-quarter degree (15') latitude. This grid is repeated on nearly all subsequent maps to give the reader an adequate frame of reference for locating the same feature on different maps.

Figure *.3 is a map of the land-surface form [Figure 2.3]. The information presented in Sections 1.6 and 1.8 indicates how the land-surface form is used to designate the terrain features considered to have a typical good exposure to the wind. Awareness of what constitutes well-exposed terrain features is crucial to the proper interpretation of the maps of wind power density.

Figures *.4 and *.5 identify and locate wind data sites relevant to the assessment. All locations in each state for which the National Climatic Center (NCC) has wind data in its archives are shown and named in Figure *.4. However, this assessment is based on a subset of NCC data augmented by data from other sources (see Sections 1.1 and 1.2). Figure *.5 shows the location

of all wind data sites used in the assessment. Sections 1.3 through 1.5 briefly describe the methods used to analyze the wind data and evaluate the wind power.

The wind energy resource for a state is illustrated using several maps. The wind power maps represent a careful synthesis of quantitative wind data guided by state-of-the-art concepts on air flow near the earth's surface. Section 1.6 describes how the analysis of the wind data is transformed into the map of annual average wind power density found in Figure *.6 [Figure 2.4]. This map gives the annual average wind power density at typically exposed sites. A discussion of the classes of wind power density in Section 1.7 gives the relationship between mean wind power density (watts/m^2) and mean wind speed (m/s or mph).

A certainty rating is used to provide a measure of the ability to objectively evaluate the wind resource in a grid cell. The certainty ratings are given in the maps of Figure *.7. The degree of certainty with which the wind power can be estimated depends on the quality and quantity of wind data, the complexity of the terrain and concern over the variability of the wind resource over short distances. How these factors are combined to assign a certainty rating is discussed in Section 1.9.

The terrain feature with typical good exposure to the wind in a particular land-surface form provides a convenient and essential reference point on which to base the analyses of the wind resource shown in Figure *.6. However, a substantial portion of the terrain may have poorer than typical exposure to the wind and will have a lower wind resource than shown on the wind power maps. The maps of Figure *.8 provide an estimate of the percentage of area in each grid cell that may experience at least each of four different wind power classes. Section 1.10 discusses the assumptions underlying the evaluation of the areal distribution of the wind resource. The area of the state estimated to experience a particular wind power class is given in Table *.1 [Table 2.2]. This table summarizes the contribution made by each grid cell to the areal distribution of wind power for the state.

The annual average wind power density compresses into a single statistic time-varying trends on several time scales, e.g., annual, seasonal, monthly, and daily. In this atlas, the seasonal evolution of the geographical distribution of wind power is shown at the state level. The maps of Figure *.9 give the average wind power density for winter, spring, summer, and autumn. The interpretation of the seasonal average wind power maps is identical to that for the annual average wind power map. [For the region, Figure 2.5 shows only the season of maximum power.]

Additional information on the time variation and other characteristics of the wind resource in each state is presented for selected locations for which the National Climatic Center placed 1-hourly or 3-hourly time-series data on magnetic tape. Descriptions of the characteristics of the wind resource presented for these stations are given in Section 3.2. The urge to consider information pertaining to one of these sites as representative of some other location must be tempered with the realization that wind characteristics are extremely site-dependent. The degree of correspondence between the wind characteristics at one site and those at another site depends on the similarity between the topographical setting of the sites, the weather patterns that affect the sites and the obstructions to the wind in the vicinity of the sites.

Table *.2 identifies the stations, and gives their location (see also Figures *.4 and *.5) and annual average wind speed and power density. Figure *.10 shows how the yearly mean speed and power varied during the period of record. The monthly mean wind speed and power over the course of a year are shown in Figure *.11. The hourly mean wind speed over the course of a day is shown in Figure *.12 with a separate curve for each season. Figures *.11 and *.12 indicate the time of year and time of day, respectively, the wind resource is available. Figure *.10, on the other hand, indicates the year-to-year variability that might be expected in the yearly mean resource.

The frequency of occurrence of winds from a particular direction and of winds with a particular speed is shown in Figures *.13 and *.14, respectively. The information on wind direction may be important in assessing the availability of the wind resource relative to surrounding terrain or nearby obstructions. However, it is also important to realize that the wind direction statistics are highly dependent on the location of the instrument site relative to obstructions and major terrain features, e.g., valleys, ridges, and mountain ranges.

Figures *.15 and *.16 portray speed and power frequency statistics in the form of speed and power exceedance curves, respectively. The fraction of the total period of record the speed equals or exceeds a given value is shown in Figure *.15. The power exceedance curve in Figure *.16 gives the fraction of the period of record for which the power exceeds a given value.

As has been shown in the preceding discussion, the order of presentation of the wind resource in this atlas proceeds from a regional perspective in Chapter 2, to a state perspective in the first part of each state chapter, to individual station descriptions in the last part of the state chapters. Attention given to Chapter 1 and Chapter 3 will make it possible for the reader to properly interpret the wind resource presentations.

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CHAPTER 1: REGIONAL WIND ENERGY RESOURCE ASSESSMENT

Rapid development of wind as a source of commercial electric power is the principal goal of the Federal Wind Energy Program. Utility planning, wind turbine manufacturing and marketing of wind energy conversion systems all depend on detailed wind resource assessments. This atlas of the Northwest's wind resource, a product of the Wind Characteristics Program Element of the Federal Wind Energy Program, represents a major source of information for meeting these various needs.

This wind energy resource atlas is the first of twelve such atlases that will be assembled. The other atlases will describe the potential wind resource in eleven other regions of the United States (see Figure 1.1). The spatial and temporal resolution of the wind resource in these regional assessments will be depicted in considerably greater detail than that in existing national assessments (Reed 1975, Coty 1976, Garate 1977, Elliott 1977). To produce the Northwest atlas in a timely fashion, only existing relevant data were used. The other atlases will use comparable data sets, analysis techniques and presentations to ensure the comparability of the wind resource assessments.

The Northwest atlas assimilates six collections of wind resource data: one for the region and one for each of the five states that compose the Northwest region (Idaho, Montana, Oregon, Washington, and Wyoming). At the state level, features of the climate, topography and wind resource are discussed in greater detail than is provided in the regional discussion, and the data locations on which the assessment is based are mapped. Variations, over several time scales, in the wind resource at selected stations in each state are shown on graphs of monthly average and interannual wind speed and power, and hourly average wind speed for each season. Other graphs present speed, direction and duration frequencies of the wind at these locations.

The methods used to identify, screen, evaluate, and analyze the various types of data, and to produce the wind energy resource

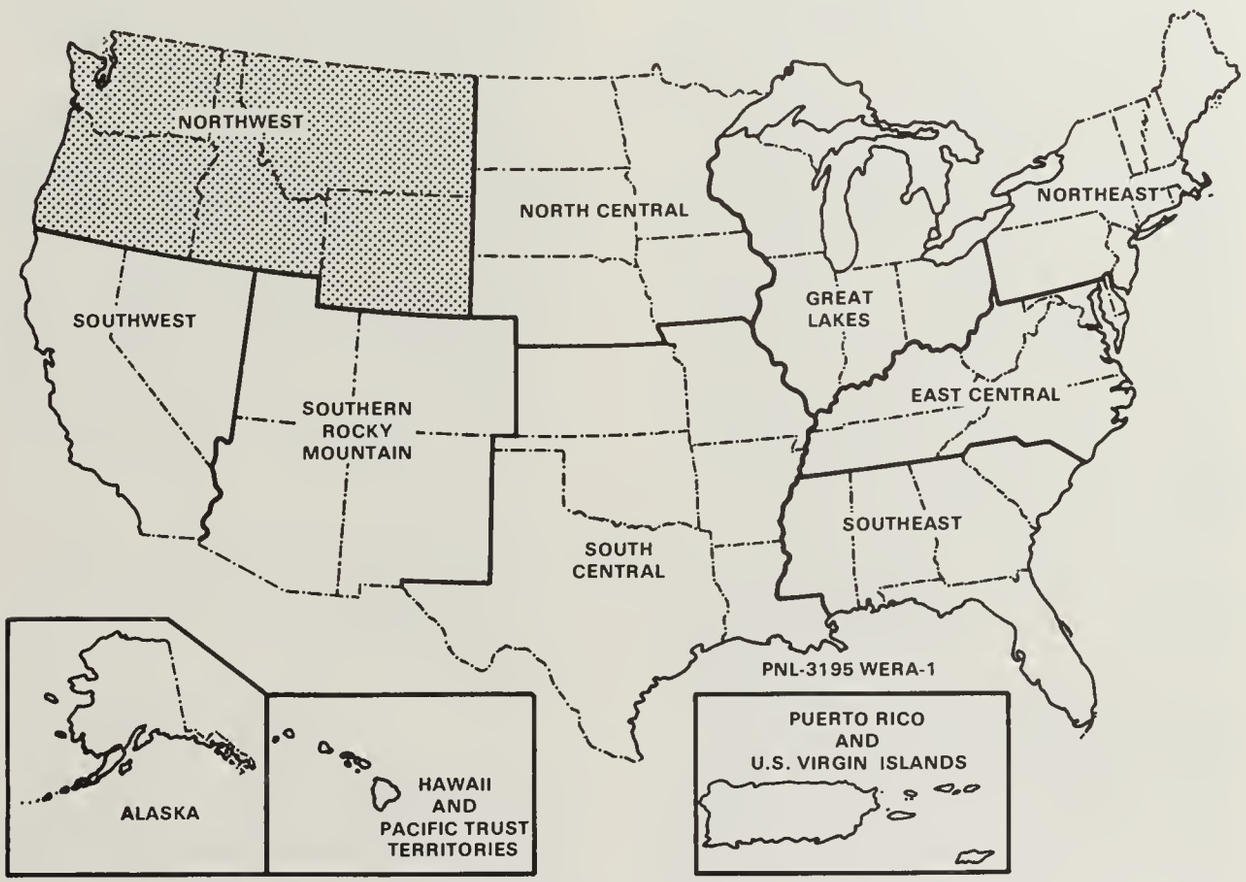


FIGURE 1.1. Geographic Divisions for Regional Wind Energy Assessments

maps and graphs will only be described briefly. [For more detail see Elliott and Barchet (1980)]. However, this discussion will provide the reader with useful background information for interpreting the wind energy resource maps for the Northwest.

1.1 IDENTIFICATION OF WIND DATA SOURCES

The surface wind data on which this atlas has been based were obtained from several sources: the National Climatic Center (NCC), the U.S. Forest Service, university research projects, nuclear and fossil-fuel power plants and their proposed sites, DOE candidate wind turbine sites, the Atmospheric Environment Service of Canada, and other government and private organizations. The National Climatic Center offers the largest collection of wind data. Surveys and indices of wind data archived at the NCC (Changery 1975, 1978; Changery et al. 1977) are extremely helpful in locating available wind data. The Index of Original Surface Weather Records, published for each individual state by the NCC, provides additional information about stations at which wind data have been taken.

The wind data available from the NCC may be in one or more of three formats: summarized, digitized, and unsummarized. Initially, all wind data are in the unsummarized format consisting of the original station weather records. For many stations, the collection of individual observations has been condensed into wind summaries. Changery et al. (1977) present examples of the various summary formats used and indices of the stations for which wind summaries are available. For still fewer stations (primarily airport stations) the NCC has put the original one- or three-hourly weather observations on magnetic tape to create a digitized time series of weather (and wind) observations. [TDF-14 (NCC 1975) describes the data on these tapes.] Table 1.1 indicates the number of stations with wind data in these various formats in the Northwest.

Conventional NCC surface weather data in coastal areas were supplemented by monthly mean wind speeds summarized over one-degree latitude by one-degree longitude squares for the West Coast in the Climatic Study of the Near Coastal Zone (National Weather Surface Detachment 1976). Wind summaries at the 150-m and 300-m levels above the surface (Winds Aloft Summaries, NCC 1970) for 8 sites in the Northwest supplemented the upper-air wind climatology compiled by Crutcher (1959) for the northern hemisphere.

In contrast to the NCC data, which are primarily from inhabited areas, U.S. Forest Service data in the National Fire Weather Data Library (Furman and Brink 1975) are from remote sites in mountainous and forested areas under the jurisdiction of the Federal government (i.e., national forests, national parks, Indian reservations, or Bureau of Land Management areas). Nearly 700 stations with wind data are reported in the National Fire Weather Data Library for the Northwest (Marlatt et al. 1979). However, only one afternoon observation, at about 2 p.m., is digitized per day during the local fire weather season.

Wind data from 10 nuclear or fossil-fuel power plants or potential plant sites (Verholek 1977) were examined. Many other wind data sets collected by university research projects, state and local air pollution control agencies, or in support of environmental impact statements have also been identified (Hewson et al. 1978; Marwitz and Gilkey 1979).

1.2 WIND DATA SCREENING

Table 1.1 indicates the quantity of wind data available in the Northwest. However, not all of these data need to, or should, be used in a wind resource assessment. Screening procedures were developed to identify stations with the most useful data and to eliminate stations that would not significantly contribute information on the distribution of the wind resource.

TABLE 1.1. Stations with Wind Data in the Northwest and Peripheral Area Screened in Assessment

Source and Type	Screened	Retained
National Climatic Center		
Digitized	97	61
Summarized	205	173
Unsummarized	207	80
National Fire Weather Data Library	685	63
Nuclear & Fossil-Fuel Power Plant	10	10
University Research	26	26
Other	16	16
Canadian	34	34

Wind data in summarized or digitized format were chosen over unsummarized data. When stations had both summarized and digitized data, the digitized data were used for selected stations to prepare a more extensive characterization of the wind

resource. Unsummarized data were used only when no summarized or digitized data were available.

In areas with a high density of stations with wind summaries, those stations appearing to have the best exposure to the wind, greatest number of daily observations, longest period of record, and longest period of unchanged anemometer height and location were usually selected over other nearby stations. When more than one type of summary (see Changery et al. 1977) was available for a given station, the summary covering the longest period of record with constant anemometer height and location, with the greatest number of wind speed and direction classes, and with the highest frequency of daily observations was chosen.

The screening of the National Fire Weather Data Library by Marlatt et al. (1979) identified those stations where $\geq$ 70% of the once-daily observations exceeded $\overline{3}$.5 m/s. This significantly reduced the number of U.S. Forest Service sites to be considered in the assessment. Table 1.1 shows the effect of screening on the number of sites analyzed. Only sites for which there was quality information pertaining to the wind resource were retained for the final analysis.

1.3 TIME SCALES IN REGIONAL ASSESSMENTS

Several time scales are encountered in the following discussions of the wind resource: annual, seasonal, monthly and diurnal. Annual mean values are generally based on an average of the one- or three-hourly observations of wind speed or power in the period of record; however, a complete calendar year's data (covering January 1 to December 31) is used for calculating individual yearly means. At stations with less than 24 hourly observations or 8 three-hourly observations per day, the values are only representative of the times of day for which the data were taken.

The four seasons are defined as:

- winter - December, January and February
- spring - March, April and May
- summer - June, July and August
- autumn - September, October and November.

The phrase "seasonal trends" refers to the change in monthly mean values over the course of the four seasons.

Monthly mean values are based on as many hours of data as are available for that month in each year of the period of record.

The daily or diurnal cycles of variation in the hourly mean wind power or speed are referenced to local standard time on a 24-hour clock. Midnight is both 00 and 24.

1.4 EVALUATION OF WIND DATA

For the purpose of mapping the geographical variation of the wind resource, wind power density was chosen over wind speed since the power density incorporates in a single number the combined effect of the distribution of wind speeds and the dependence of the power density on air density and on the cube of the wind speed. Quantitative wind data in three formats were evaluated for mean wind power density: digitized, summarized, and unsummarized. The average wind power density $\overline{P}$ (watts/m^2) in a vertical plane perpendicular to the wind direction for stations with one- or three-hourly digitized data was calculated from:

$$\overline{P} = \frac{1}{2n} \sum_{i=1}^{n} \rho_i V_i^3 \qquad (1)$$

where

n = the number of observations in the averaging period

ρ_i = the density (in kg/m^3) computed from the station pressure and temperature

V_i = the wind speed (in m/s) at the ith observation time.

For stations with wind summaries, $\overline{P}$ was calculated from:

$$\overline{P} = \frac{1}{2} \overline{\rho} \sum_{j=1}^{c} f_j V_j^3 \qquad (2)$$

where

$\overline{\rho}$ = the mean air density

c = the number of wind speed classes

f_j = frequency of occurrence of winds in the jth class

V_j = the median wind speed of the jth class.

In those cases for which unsummarized wind data were assessed, the seasonal and annual average speeds, $\overline{V}$, were estimated from a visual examination of one year's original weather records. The wind power density, $\overline{P}$, was then estimated by assuming the speed frequency distribution followed a Rayleigh distribution (Cliff 1977):

$$\overline{P} = 0.955\ \overline{\rho}\ \overline{V}^3 \qquad (3)$$

1.4.1 Vertical Adjustment

The anemometer height above the surface rarely was at either the 10-m or 50-m reference levels chosen for the presentation of the wind resource. A power law was used to adjust the long-term mean wind speed or power density to the reference level:

$$\frac{\overline{V}_r}{\overline{V}_a} = \left(\frac{Z_r}{Z_a}\right)^{\alpha} \quad \text{or} \quad \frac{\overline{P}_r}{\overline{P}_a} = \left(\frac{Z_r}{Z_a}\right)^{3\alpha} \qquad (4)$$

where

$\overline{V}_{a,r}$ and $\overline{P}_{a,r}$ = the mean wind speed or wind power density at heights $Z_{a,r}$ (the anemometer and reference level, respectively)

α = the power law exponent.

An examination of long-term mean wind speeds at airport locations at which the anemometer height was changed and at tower sites with multiple levels of anemometry indicates an $\alpha \sim 1/7$ to be widely applicable to low surface roughness and well exposed sites from which conventional NCC data are available (Elliott 1979b).

1.4.2 Estimates for Mountainous Areas

The quantitative estimation of wind power over mountains made use of the northern hemisphere upper-air wind climatologies for the 850, 700 and 500 mb constant pressure levels by Crutcher (1959). Since earlier studies had shown a strong correlation between mountaintop and free-air wind speeds (Wahl 1966), the free air wind speed at mountain summit or ridge crest height was extrapolated (or interpolated) from the mean scalar speeds on the constant pressure surfaces. Estimates of the mountaintop wind speeds were made on a grid one-fourth degree latitude by one-third degree longitude. In each such cell of the grid over mountainous areas, the mean ridge crest or mountain summit elevation and appropriate constant pressure surface mean wind speeds were estimated. Linear extrapolation provided the mean free-air wind speed at the terrain elevation and the application of a Rayleigh speed distribution gave the mean free-air wind power. The mean wind power at the 10-m and 50-m reference heights was taken to be one-third and two-thirds of the free-air value, respectively, to account for the frictional slowing of the wind near the surface.

These estimates are considered lower limits for exposed ridge crests and mountain summits. Local terrain features in these mountainous regions can enhance the wind power considerably. However, a major uncertainty in mountainous terrain is the representativeness of some of the data upon which the free air estimates are based (e.g., sheltering by nearby mountains can bias rawinsonde winds).

Wherever possible, these estimates were compared with surface data from ridge crests and mountain summits. Over some of the mountainous areas, the estimates were adjusted based on the location of the upper-air recording station and/or the surface data from ridge crests.

1.5 QUALITATIVE WIND INDICATORS

Although more than 460 stations provided the wind resource assessment in the Northwest with quantitative data, these stations were not uniformly distributed. The station location figures for each state show that most NCC stations are located in populated areas and along transportation corridors. Large areas in the Northwest are devoid of any form of quantitative wind data suitable for this assessment, such as southeastern Oregon, eastern Idaho and western Montana, and south-central Wyoming. Furthermore in areas of complex terrain, most observation sites (except for some U.S. Forest Service fire lookout sites) are confined to valley locations. To evaluate the distribution of the wind resource in data-sparse areas, three qualitative indicators of the wind speed or power were developed for, and employed in, the assessment.

The most widely used technique depended on certain combinations of topographical and meteorological features (Elliott 1979a) that were associated with high or low wind speeds. Those features indicative of high mean wind speeds are:

- gaps, passes, and gorges in areas of frequent strong pressure gradients
- long valleys extending down from mountain ranges
- high elevation plains and plateaus
- plains and valleys with persistent strong downslope winds associated with strong pressure gradients
- exposed ridges and mountain summits in areas of strong upper-air winds

- exposed coastal sites in areas of

    1) strong upper-air winds, or
    2) strong thermal/pressure gradients.

Features that signal rather low mean wind speeds are:

- valleys perpendicular to the prevailing winds aloft
- sheltered basins
- short and/or narrow valleys and canyons
- areas of high surface roughness, e.g., forested hilly terrain.

Areas in which the appropriate features occur were determined by examining topographic contour and shaded relief maps and synoptic and climatological maps of sea-level pressure patterns and air flow.

The removal and deposition of surface materials by the wind to form playas and sand dunes indicate strong winds from a nearly constant direction. Areas in the Northwest containing eolian landforms were identified by Marrs and Kopriva (1978). Correlating characteristics of eolian features to long-term mean winds speeds has proven difficult (Marrs and Gaylord 1979). However, the distribution of eolian features was used to delineate locations with high wind energy in several data-sparse areas.

Evidence of persistent strong winds can also be found in wind-deformed vegetation. Areas with flagged trees have been identified by Hewson et al. (1978) in several areas of the Northwest. Mean wind speeds deduced from the extent and morphology of tree deformation by Hewson et al. (1979) provided useful qualitative indicators of wind speed in many data-sparse areas.

1.6 WIND POWER MAPS

The production of mean wind power density maps, such as those presented for each state, depended on the coherent synthesis of several pieces of information. The goal of the synthesis process was to present wind power density values representative of sites well exposed to the prevailing strong winds. Hilltops, ridge crests, mountain summits, large clearings and other locations free of local obstructions to the wind are expected to have good exposure to the wind (see Table 1.2). In contrast, locations in narrow valleys and canyons, downwind of hills and obstructions, or in forested or urban areas are likely to have poor exposure. The wind power density shown on the maps in this atlas will not be representative of poorly exposed locations. Estimates for ridge crests and summits (the shaded areas on the maps) are lower limits to the wind power expected at exposed sites. In such areas, local terrain features can enhance the wind power considerably (e.g., by a factor of 2 or 3). By specifying the type of wind exposure to which the map values of wind power pertain, we avoid the ambiguity that typical-location or average-for-the-terrain values might introduce. In this atlas, the terms wind energy, wind power and wind power density are used synonymously.

To represent the wind resource at well-exposed sites, it was necessary to become extremely familiar with the land-surface form and topography in the vicinity of every data site. Maps were prepared showing the location of stations, the mean wind speed and mean wind power at the reference level, the character of anemometer exposure, and the land-surface form for each state. On these maps, areas with the appropriate combinations of topographical and meteorological features were identified, areas with eolian landforms were outlined, and areas with wind-deformed vegetation were denoted. A great deal of attention was given to the orientation of topographic features with the prevailing wind directions. Only after all this information was assembled were the maps analyzed. The annual maps for each state were merged into a regional mosaic.

1.7 WIND POWER DENSITY CLASSES

The analysis of wind power maps departs from conventional isopleth analyses by showing the boundaries of wind power density classes. Each wind power class represents the range of wind power densities likely to be encountered at exposed sites within an area designated as having that wind power class. Table 1.3 gives the power density limits for the wind power classes used in the atlas for the 10-m (33-ft) and 50-m (164-ft) reference levels. The definitions of the wind power density classes are repeated with the annual wind power map for the region and for each state as a convenience for the reader.

Wind power density is proportional to the third moment of the wind speed distribution and to air density; therefore, a unique correspondence between power density and mean wind speed (the first moment of the speed distribution) does not exist. However, by specifying a Rayleigh wind speed distribution and a standard sea level air density (1.22 kg/m^3) a mean wind speed can be determined for each wind power class limit. The decrease of air density with elevation requires the mean Rayleigh speed to increase by about 3%/1,000 m elevation (1%/1,000 ft) to maintain the same power

density. If the wind speed distribution is more sharply peaked than the Rayleigh distribution, the equivalent mean speed will be slightly higher than the value in Table 1.3. Conversely, a broader distribution of wind speeds will slightly reduce the equivalent mean speed.

1.8 CLASSES OF LAND-SURFACE FORM

The physical characteristics of the land-surface form affect the number of wind turbines that can be sited in exposed places. For example, over 90% of the land area in a flat plain may be favorably exposed to the wind; whereas in mountainous terrain only the ridge crests and passes, which may be only a small percentage (<5%) of the land area, may represent exposed sites. The map of classes of land-surface form by Hammond (1964) provided information on the distribution of plains, tablelands, hills and mountains in the Northwest. Several characteristics are coded on this map:

- percentage of land area occupied by surfaces of gentle inclination (less than 8% slope)
- local relief, the maximum difference in elevation within a unit square six miles across
- percentage of gently inclined surfaces that lie in the lower half of the local relief
- land area covered by sand, ice, and standing water
- pattern of major crests, peaks, and escarpments.

The first three characteristics are used in the classification scheme (see Table 1.4); the latter two have been omitted from the maps presented here. A three-character code, for example B3a, designates each class of land-surface form. In this example the "B" indicates that 50% to 80% of the area is occupied by gentle slopes; the "3" that the maximum local difference in elevation is 100 to 150 m (300 to 500 ft); and the "a" that more than 75% of the gently sloping land is in the lowland. In areas of very little gentle slope (D) or very low relief and great smoothness (A1), the third designator is omitted.

For each land-surface form, the percentage of land area that is representative of well exposed, moderately exposed, and poorly exposed sites has been estimated. These percentages were determined subjectively as a function of the slope, local relief, and profile type. Table 1.2 gives the average percentage of land area that is designated as exposed terrain for the different classes of land-surface form. For simplicity, the percentages shown for each class of land-surface form have been averaged over the range of categories in local relief and profile type found in the Northwest. For example, the 27% for open hills is an average for C2 through C4. The average percentage of land area that is designated as exposed terrain ranges from 93% in smooth plains to 3% in mountainous areas where the exposed areas are usually the ridge crests and mountain summits.

1.9 CERTAINTY RATING

The analyses of wind power density at exposed sites shown on the wind power maps depend on the subjective integration of several factors: quantitative wind data, qualitative indicators of wind speed or power, the characteristics of exposed sites in various terrain and familiarity with the meteorology, climatology and topography of the region. As a result, the degree of certainty with which the wind power class can be specified depends on

- the abundance and quality of wind data
- the complexity of the terrain
- the geographical variability of the resource.

A certainty rating from 1 (low) to 4 (high), of the wind energy resource estimate has been made for each cell of a one-quarter degree latitude by one-third degree longitude grid on a state-by-state basis by considering the influence of the above three factors on the certainty of the estimate of the wind power class for each cell. The definitions for the certainty ratings are adopted from those used by Voelker et al. (1979) in a resource assessment of U.S. Forest Service tracts. The certainty ratings for the wind resource assessment are defined as follows:

Rating	Definition
1	The lowest degree of certainty. A combination of the following conditions exists: 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.

Rating	Definition
2	A low-intermediate degree of certainty. One of the following conditions exists: 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	A high-intermediate degree of certainty. One of the following conditions exists: 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.

The assignment of a certainty rating requires subjective evaluation of the interaction of the factors involved.

1.10 AREAL DISTRIBUTION OF THE WIND RESOURCE

As noted above, the wind power density class values shown on the maps apply only to sites well exposed to the wind. Therefore, the map area designated as having a particular wind power class does not indicate the true land area experiencing this wind power. Instead, there is a complicated and difficult-to-quantify relationship among the class of land-surface form, the land-surface area and the map value of wind power density. For each land-surface form, the fraction of land area that would be favorably exposed to the winds, i.e., have the wind power density indicated on the map, was estimated (see Table 1.2 for averages in various land-surface forms). Furthermore, to be able to establish a wind power density for the remaining area, it was also necessary to specify a factor by which the wind power shown on the map is reduced in the less exposed areas. As an additional complication, some land-surface forms, isolated hills and ridges that rise above a nearly flat landscape may even experience a higher power density than the map indicates.

To accommodate these various situations, the land area represented by a given land-surface form was divided into four exposure categories: 1) better exposure than typical for the terrain, 2) exposure typical for that land-surface form, 3) partially sheltered exposure, and 4) very sheltered exposure. The partitioning of the land-surface forms into the four categories was based on the parameters used to classify the land-surface forms and on the experience of the authors and their co-workers with the terrain represented by the land-surface forms.

In order to adjust the wind power density from the map value to the various exposure categories, the power density was scaled to be 1) greater than, 2) equal to, 3) slightly less than, and 4) much less than the map value power density. The factor by which the map value was adjusted to represent the wind power density in each category was determined by the magnitude of elevation relief given by the middle character of the land-surface form code. (The minimum power density allowed for a category was the median value of wind power density class 1). The scaling factors for the wind power density were based on a conservative application of a power-law type vertical adjustment with the height change specified by the terrain relief code.

In each cell of a grid one-third degree longitude by one-quarter degree latitude, the land-surface form was specified and the wind power class associated with a typically exposed site in that land-surface form was determined. By partitioning the area of the cell into the four exposure categories, and by scaling the wind power class to each category, the contribution of that cell to the areal distribution was determined.

A cell-by-cell representation of the areal distribution is given in a map that indicates the percentage land area in a cell over which the wind power class equals or exceeds a threshold value. Four maps are shown in the chapters on the state wind resources for threshold values of classes 2, 3, 4 and 5.

A summary table of the areal distribution that combines the contributions by each cell is provided for the region and for each state. For each power class, the sum of the area contributed by each exposure category is determined for each state and the region. Summing the area associated with each power class in each cell gives the area of the state or region over which the power class exceeds a given value. The table gives the estimated land area (km^2) and the percentage of land area associated with each power class.

Both of these presentations of the areal distribution of the wind resource are highly dependent on the estimates used to partition the land area into the four exposure categories and on the scaling of the power density for each category of exposure. Therefore, the areal distribution derived from the wind power and land-surface form maps must be considered only an approximation. The quantity and quality of wind data and topographic information required to make a highly accurate cell-by-cell appraisal of the wind resource goes far beyond the scope of this regional wind resource assessment. However, as wind information becomes available through new measurement programs or through the discovery and processing of existing data sets, the evaluation of the areal distribution of the wind resource can be improved on a cell-by-cell basis.

TABLE 1.2. Land-Surface Form Terrain Features Representative of Exposed Locations

Land-Surface Form	Exposed Feature (Map Value)	Percentage Area[a]
Plains: A1; B1,2	Plains	93
Plains With Hills: A, B3a,b	Open Plains	79
Plains With Mountains: B4-6a,b	Plains (not shaded)[b]	67
	Ridge Crests and Mountain Summits (shaded)	10
Tablelands: B3-6c,d	Tablelands, uplands	80
Open Hills: C2-4	Hilltops and Uplands	27
Open Mountains: C5-6	Broad Valleys (not shaded)	80
	Ridge Crests and Mountain Summits (shaded)	12
Hills: D3-4	Hilltops and Uplands	9
Mountains: D5-6	Ridge Crests and Mountain Summits (shaded)	3

[a] Percentage represents an average over the land-surface forms found in the Northwest region.
[b] Shaded areas on the wind maps, emphasize that map values are estimates for ridge crests and mountain summit locations.

CHAPTER 2: REGIONAL FEATURES

In this chapter, the geography, climate, annual average wind power and seasonal variations in the wind power are described for the Northwest region. Assessments of the wind resource for each state of the Northwest were performed using the methods described in Chapter 1. These assessments were then combined to depict the wind energy potential for the region. Major areas in the Northwest that are estimated to have the greatest wind resource are also described in this chapter.

2.1 GEOGRAPHY AND TOPOGRAPHY

The Northwest region, consisting of Idaho, Montana, Oregon, Washington, and Wyoming, covers more than 1,250,000 km^2 (490,000 mi^2) and had a total population of 7,244,617 in 1970 (see Table 2.1). Almost half of the region's people live in western Washington and Oregon, where the region's two largest cities--Seattle and Portland--are located. The major cities, rivers, mountain ranges, and national parks are shown in Figure 2.1.

TABLE 2.1. Land Area and Population of the Northwest

State	Area km^2	Area (mi^2)	Population in 1970	Population Per km^2 (mi^2)
Idaho	216,412	(83,557)	713,015	3.3 (8.5)
Montana	381,087	(147,138)	694,409	1.8 (4.7)
Oregon	251,180	(96,981)	2,091,533	8.3 (21.6)
Washington	176,617	(68,192)	2,413,244	19.4 (50.1)
Wyoming	253,597	(97,914)	332,416	1.3 (3.4)
Northwest	1,278,895	(493,782)	7,244,617	5.7 (14.7)

The topography varies dramatically throughout the Northwest, which is dissected by the Cascade Range in the western part of the region and by the Rocky Mountains in the central and eastern parts of the region (see Figure 2.2). Over one-third of the region's terrain is hilly and mountainous. Although there are no extensive flat or smooth plains, many tablelands and plains with isolated hills exist (see Figure 2.3), where a large fraction of the land area appears favorably exposed to the wind. These latter conditions are found in much of eastern Montana, eastern and southern Wyoming, and the Snake River plain of southern Idaho.

2.2 CLIMATE

The mountain ranges of the Northwest significantly affect the climate. West of the Cascade Range, the relatively mild winters and cool summers indicate a maritime climate. The prevailing winds aloft are primarily westerly from the Pacific Ocean. However, the Cascade Range, averaging 1,500 to 2,500 m (5,000 to 8,000 ft), provides a barrier to the marine air flowing into eastern Washington and Oregon from the Pacific Ocean. Desert conditions exist in the basins and valleys east of the Cascade Range. The climate east of the Cascade Range is of a continental nature, except for greater precipitation over the mountainous areas.

Winters are coldest over the Great Plains east of the Rocky Mountains and over the intermountain areas of Idaho, Montana, and Wyoming. Winters are comparatively milder in eastern Washington and Oregon, as the Rocky Mountains help shield these areas from the frequent intrusions of cold arctic air. Western Washington and Oregon are even milder as the Cascade Range blocks the penetration of cold air intrusions from the east.

Summers are cool along the Oregon and Washington coast; average daytime high temperatures for July are 17 to 23°C (65 to 75°F). The sea surface temperatures along the Oregon coast remain quite low (10 to 15°C or 50 to 60°F) even during the summer months because of upwelling of the coastal waters. Average highs for July are about 25°C (75 to 80°F) in the Puget Sound area and about 28°C (80 to 85°F) in the Willamette River valley. In the basins and on the plateaus from the Cascades east to the Great Plains, average high temperatures for July are generally 28 to 35°C (80 to 95°F), depending on elevation.

Annual precipitation varies from nearly 450 cm (180 in.) on Washington's Olympic Peninsula to less than 20 cm (8 in.) in parts of eastern Washington, southern Idaho and Wyoming. Orographic lifting results in heavy precipitation along the western slopes of the Cascades. Similarly, orographic precipitation occurs over the Blue and Rocky Mountains. The season of maximum rainfall varies markedly throughout the region, from a winter maximum in western Washington and Oregon to a late spring and early summer maximum in eastern Montana and Wyoming.

2.3 WIND POWER IN THE NORTHWEST

The annual average available wind power density in the Northwest is shown in Figure 2.4. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as mountain summits, ridge crests, hilltops, and uplands (see Section 1.6). However, nearby terrain features may interact with the windfield to cause the wind power at some exposed sites to vary as much as ±50 to 100% from the assessment value. (See Wegley et al. 1980 for information on terrain features that may increase or reduce wind energy.) In forested or wooded areas, the assessment values are representative of large clearings, such as airports, with good exposure to the prevailing strong winds. In mountainous regions, the analyses also reflect major valleys. The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (Section 1.8).

The high wind resource areas (class 4 and higher) of the Northwest can be dispersed over large areas such as on the mountain summits and ridge crests of the Cascade Range and Rocky Mountains, or they can be confined to particular topographic features such as the Columbia River gorge along the Oregon-Washington border or the Great Divide basin of Wyoming. It is convenient to refer to the latter areas as wind corridors.

A wind corridor is a passageway of lower elevation than the surrounding terrain through which the winds are channeled and sometimes enhanced. However, only those gaps, passes, valleys, gorges or canyons in which the meteorological conditions cause high wind speeds are referred to as wind corridors (Elliott 1979a). A corridor may vary in width from just a few kilometers (e.g., the Columbia River gorge along the Oregon-Washington border) to over 100 km (e.g., the Great Divide Basin in south-central Wyoming).

A brief description of the major (class 4 and higher) wind resource areas follows in Section 2.5. For more complete discussions of these wind resource areas, refer to the chapter on the state containing these areas.

2.3.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power resource were assigned to each grid cell as described in Section 1.9. Maps of the certainty rating in each state accompany the descriptions of that state's wind resource.

The geographical distribution of the certainty ratings ranges from low (1) to high (4). Only a few areas in the Northwest are assigned a high certainty. These areas include much of the Puget Sound area of Washington, the Willamette River valley of Oregon, the Snake River plain of Idaho, and portions of the plains in Montana and southern Wyoming. A high certainty rating is assigned to these areas because of the availability of existing data, low complexity of terrain, and low spatial variability of the resource. The only areas with both a high wind resource (power class 4 or higher) and a high certainty are the vicinity of Cut Bank and Great Falls, Montana and parts of southern Wyoming. Most areas with nonmountainous terrain in the Northwest are given certainty ratings of 2 and 3. However, a large area in southeastern Oregon has a low certainty rating primarily because of the sparsity of data and high complexity of the terrain.

Year-round data are available from only a few exposed sites in mountainous terrain. Nevertheless, the mountain summit and ridge crest estimates are given a certainty rating of 2 because upper-air wind data were used to approximate the power in these areas.

2.3.2 Areal Distribution

Through the superposition of a grid one-third degree longitude by one-quarter degree latitude over the region, the areal distribution of wind power can be computed as described in Section 1.10. Of the 1794 grid cells into which the Northwest region is divided, 895 have exposed areas with class 4 or higher wind power. However, these power classes are predominantly assigned to ridge crests and mountain summits in mountainous areas (shaded areas on the maps) with high topographic relief. As a result, the estimate of the actual fraction of land area that experiences class 4 and higher wind power (about 10%) is significantly less than the 50% suggested by the wind power map of Figure 2.4. In contrast to the effect of terrain on the area with high power classes, the land area estimated to have low power density (about 76% for the region), class 1 and 2, is much larger than the wind power maps suggest (24%).

Table 2.2 summarizes the results of the computation of the areal distribution for the states of the Northwest region. The subjectivity underlying the assignment of exposure partitioning and power scaling warrants reporting the areas and percentages to only two significant digits (see Section 1.10). Thus, individual areas and percentages may not sum to their stated totals.

Of the upper four wind power classes, class 4 gives the highest area contribution primarily because of the large expanse of tablelands and hilly plains areas in Wyoming and Montana with this power class.

In contrast, power classes 5 and 6 are infrequently associated with plains areas, except over the northwestern plains of Montana and central Wyoming. Thus, although the wind power map (Figure 2.4) shows about 27% of its area with classes 5 and 6, the actual land area with these power classes is estimated to amount to only about 3% for the region. The influence of the windy plains is evident in the roughly 5% value found in Montana and Wyoming for those power classes.

Class 7 wind power occurs in Wyoming because of the assumption that locations with exposures that enhance the wind through a speedup effect over appropriately sloping ridges or through channeling between topographic barriers are likely to occupy about 5% of the area in hilly plains.

2.4 SEASONAL VARIATIONS IN THE WIND RESOURCE

Throughout most of the Northwest, winter and spring are seasons of maximum wind power (see Figure 2.5). Areas with a winter maximum include western Washington and Oregon, southern Wyoming, central Montana east of the Rockies, the southwest Montana wind corridors, and exposed mountain summits and ridge crests throughout the Northwest. At exposed mountain summits and ridge crests, winter is the season of maximum wind power because mean upper-air wind speeds (over 1,500 m above ground level) are strongest during the winter (December, January and February). However, mean winter wind speeds are generally low in sheltered basins and valleys. Cold air often fills the basins and valleys, resulting in a temperature profile that may remain stable throughout the day because of low solar insolation. Under these stable atmospheric conditions, the vertical mixing is restricted, and winds may be very light in a basin or valley even if the winds are strong on nearby ridge crests.

In spring (March, April and May), the upper-air flow remains quite strong over most of the Northwest, although its strength decreases as spring progresses from March to May. Because solar insolation is greater in spring than in winter, temperature profiles are less stable and more vertical mixing in the surface layer results. Therefore, near-surface wind speeds over the valleys, basins, and plains of the Northwest are generally greater in spring than in winter, except in three locations:

- in the Puget Sound and Willamette River valley, where seasonal variations in atmospheric stability are not as great as in the interior because of the maritime climate
- east of the Montana Rockies, where strong winds are often associated with strong surface pressure gradients during the winter
- in wind corridors where the wintertime flow is channeled and intensified by the terrain and pressure gradients.

In summer (June, July and August), mean upper-air wind speeds are low to moderate (4 to 6 m/s or 8 to 12 mph) and ridge crests and mountain summits generally have only low to moderate mean wind speeds. Most valleys, basins, and plains also have low mean wind speeds. However, four areas in the Northwest experience high summer mean wind speeds: the eastern part of the Strait of Juan de Fuca, the southern and central Oregon coast, the Columbia River corridor along the Washington-Oregon border, and the central Washington corridor in the Ellensburg area.

In the autumn (September, October and November), upper-air wind speeds increase from low and moderate in September to high in November. Since autumn and spring mean upper-air wind speeds are not significantly different, the average wind power on exposed ridge crests and mountain summits for spring and autumn is estimated to be in the same power class. However, the valleys, basins, and plains have lower wind speeds in autumn than in spring, because of more stable air and less vertical mixing in autumn. Lakeview, in southcentral Oregon near the California border, is the only location in the Northwest that showed an autumn maximum based on a 4-yr average.

Seasonal variations in atmospheric stability affect the variation of wind speed with height in the Northwest. For example, in the eastern Snake River plain (see Figure 2.6), upper-air winds (e.g., at 3,000 m or 10,000 ft) are strongest in the winter and lightest in the summer. At the surface, however, the highest average wind speeds occur in the spring and are lowest in the winter. This seasonal trend in the wind profiles is typical of many of the valleys, basins, and plains in the Northwest.

2.5 MAJOR WIND RESOURCE AREAS

Major areas in the Northwest with high annual average wind power (class 4 and above) are briefly described in this section. For additional detail on these areas, refer

to chapters on the state assessments. For the locations of place names mentioned in this section, refer to the individual state maps (such as Figures 4.1 and 4.4 for Idaho).

2.5.1 Oregon and Washington Coast

The annual average wind power for exposed coastal and offshore areas of Oregon and Washington is estimated to be at least class 5. The abrupt increase in surface roughness inland from the coastline, because of vegetation and topography, rapidly attenuates the wind resource landward. During winter, the season of maximum wind power, high wind speeds are usually associated with storms and fronts moving in from the Pacific Ocean. However, during the summer, wind power is also high along the central and southern Oregon coast and is associated with the strong surface pressure gradients created by the cold water and relatively warm interior. (Airport wind data from North Bend, Oregon, and some other stations along the southern Oregon coast indicate a summer maximum of wind power, primarily because these sites are better exposed to the prevailing summer northerly winds than to the prevailing winter southerly winds. However, data from well-exposed coastal and offshore sites indicate a definite winter maximum.)

2.5.2 Columbia River Corridor

The Columbia River wind corridor straddles the Oregon-Washington state border from just east of Portland, Oregon, to just west of Boardman, Oregon (which is about 70 km or 40 mi west of Pendleton, Oregon). The Columbia River gorge provides a low-elevation connection between continental air masses in the interior of the Columbia River basin east of the Cascade Range and the maritime air of the Pacific coast. Especially strong pressure gradients develop along the Cascades and force the air to flow rapidly eastward or westward through the gorge. Summer winds blow eastward from the cool, dense maritime air west of the Cascades to the hot, less dense air in the Columbia Basin. In winter, the comparatively cold air in the Columbia Basin blows westward through the gorge. The windiest locations change with the season and are near the downwind end of the gorge.

2.5.3 Central Washington Corridor

Near Ellensburg, Washington, another breach occurs in the Cascade Range, which separates maritime and continental air. Unlike the Columbia River gorge, the central Washington corridor consists of relatively low mountain passes leading into a broad valley corridor to the east. In winter, the cold, dense air to the east of the passes occasionally becomes deep enough to spill westward into the Puget Sound. However, in late spring and summer the cool, marine air over western Washington is often deep enough to flow eastward over the passes and through this valley corridor into the Columbia Basin (Elliott 1979a). As a result, the wind resource in this valley corridor and over low ridges east of Ellensburg is high (class 6) during these two seasons. At Ellensburg, wind speeds are highest in early evening; the time of maximum wind speed is estimated to be earlier to the west and later to the east.

2.5.4 Northwest Montana Plains

The plains area eastward from the Rocky Mountains to Cut Bank and Great Falls, Montana, experiences high wind energy from October to April. Strong westerly to southwesterly winds are frequently associated with intense surface pressure gradients that are most prevalent during the winter, the season of maximum wind power. However, downslope winds from the Rockies during all seasons apparently make the wind resource greater in this area than it is farther eastward on the Montana plains. Maximum wind speeds typically occur from midafternoon in the winter to late afternoon in the summer months.

2.5.5 Southwest Montana Corridors

High wind resource areas are found in the Jefferson River valley near Whitehall, Montana, and the Yellowstone River valley near Livingston, Montana. The highest wind power is expected to occur near the mouth of each of these long valley corridors. Strong down-valley winds in these corridors are often associated with strong surface pressure gradients. The channeling effect of these valleys intensifies the winds set in motion by the pressure gradients (Elliott 1979a). Both of the valleys have pronounced seasonal variations in wind power density, with a maximum power density in the winter. Neighboring valleys and basins lacking the appropriate orientation show a significantly reduced wind resource. The data from Livingston show a diurnal pattern that depends more on the season than that found for Whitehall, although the wind speed shows an early-to-midafternoon maximum for both.

2.5.6 Southern Wyoming Corridor

An area of high wind energy extends across southern Wyoming from the Utah border on the west to the Nebraska border on the east. This zone of high wind energy can be attributed to a major gap, about 150 km wide, in the north-south barrier of

the Rocky Mountains. Prevailing westerly and southwesterly winds blow with little resistance through this gap. As a result, this is the largest region of nonmountainous terrain in the Northwest with a high wind energy resource. Winter is the season of maximum wind power, with class 6 and 7 power in exposed areas. Maximum daily wind speeds typically occur in the mid-to-late afternoon.

2.5.7 Exposed Mountain Ridges and Summits

At least class 4 or higher wind power is estimated for exposed mountain summits and ridge crests throughout the Northwest except for the Coast Range of Oregon and Washington. The map analyses present lower limits to the wind resource for exposed terrain in the mountainous areas. Average wind speeds may vary significantly from one ridge crest site to another and are primarily influenced by the height and slope of the ridge, orientation to the prevailing winds, and the proximity of other mountains and ridges. Winter is estimated to be the season of highest wind power over most mountain summits and ridge crests in the Northwest because mean upper air wind speeds are highest during this season. In contrast to valley and plain locations, the daily maximum wind speed may occur at night for many mountain summits and ridge crests.

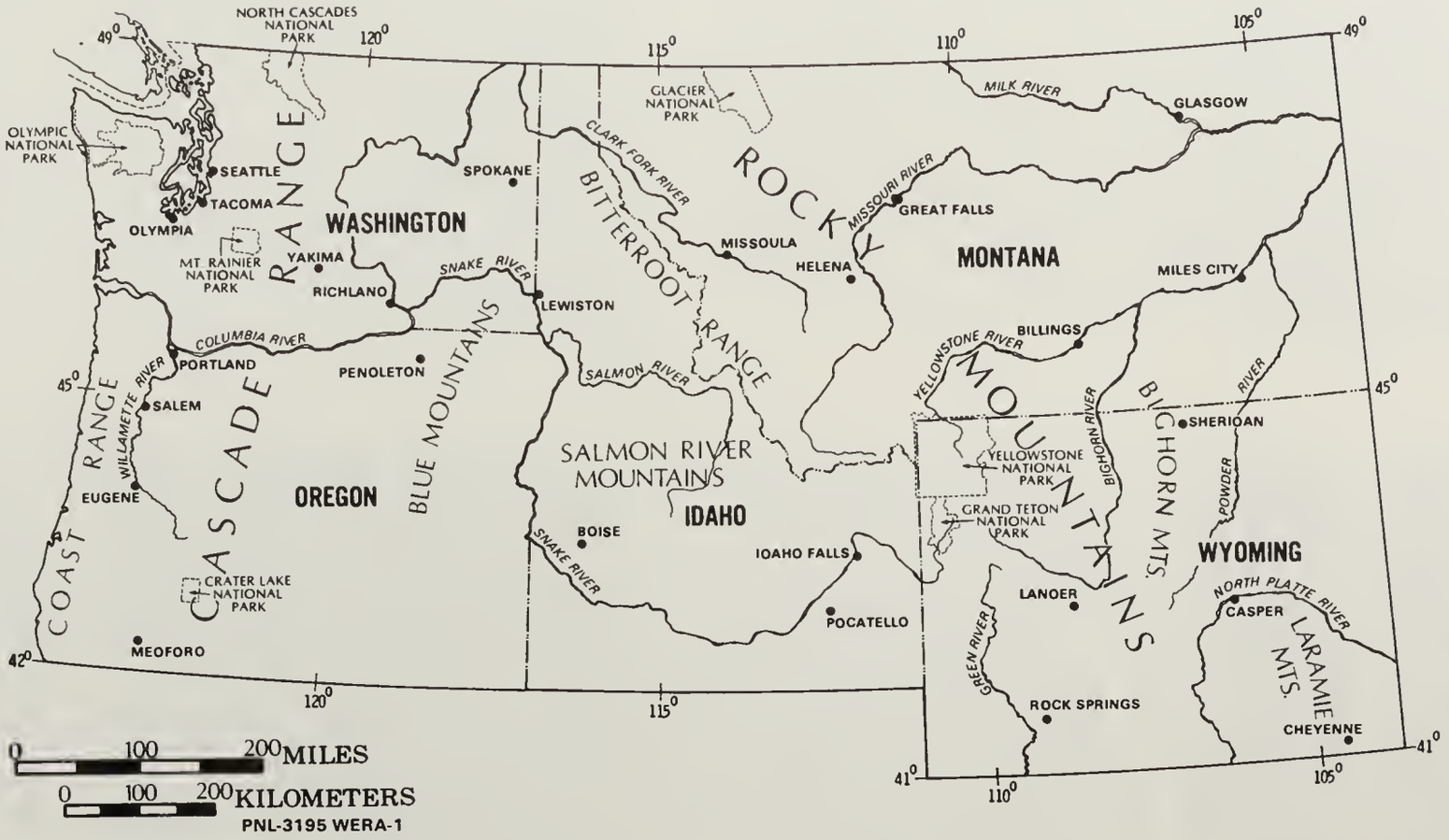


FIGURE 2.1. Geographic Map of the Northwest

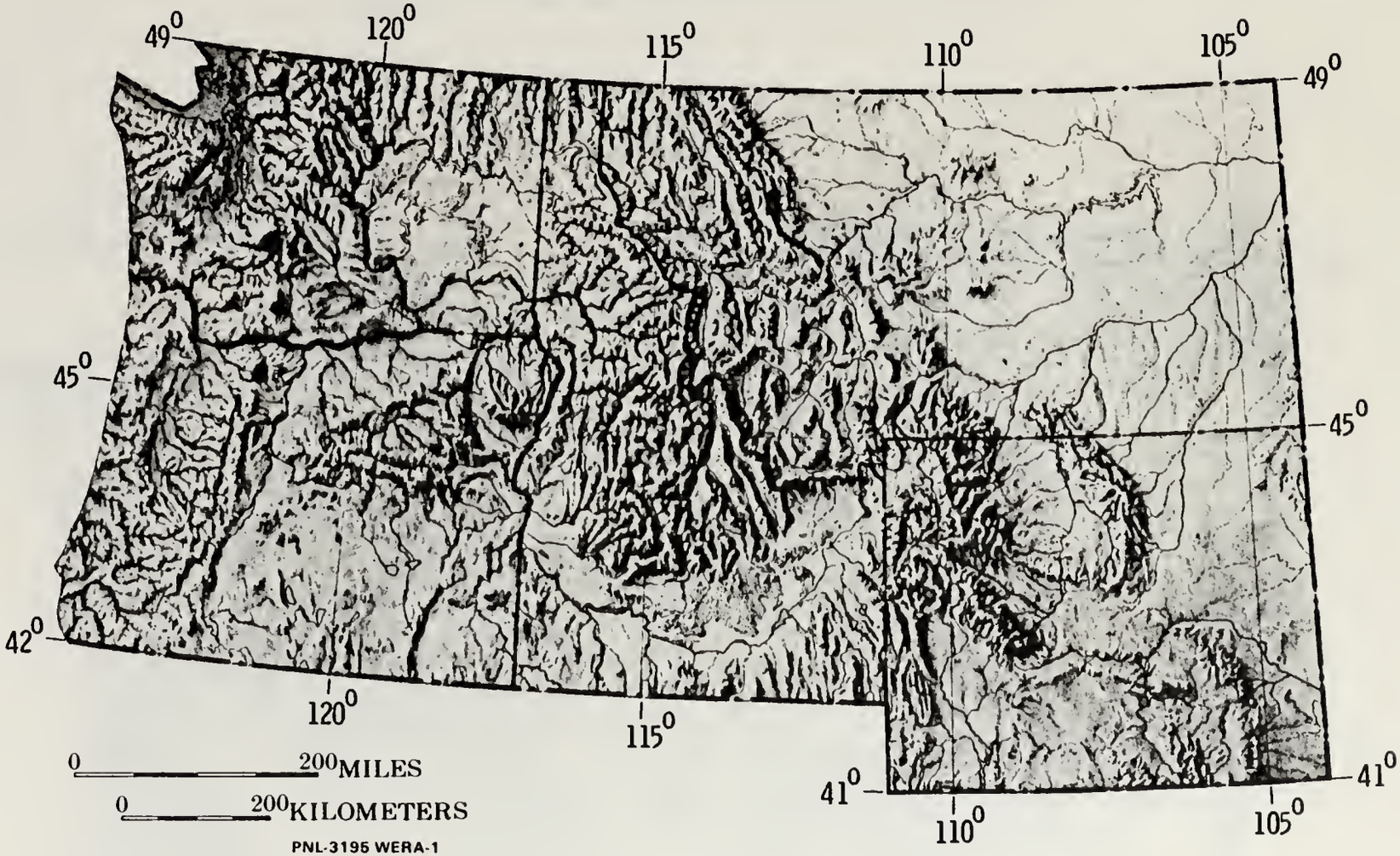


FIGURE 2.2. Topographic Map of the Northwest

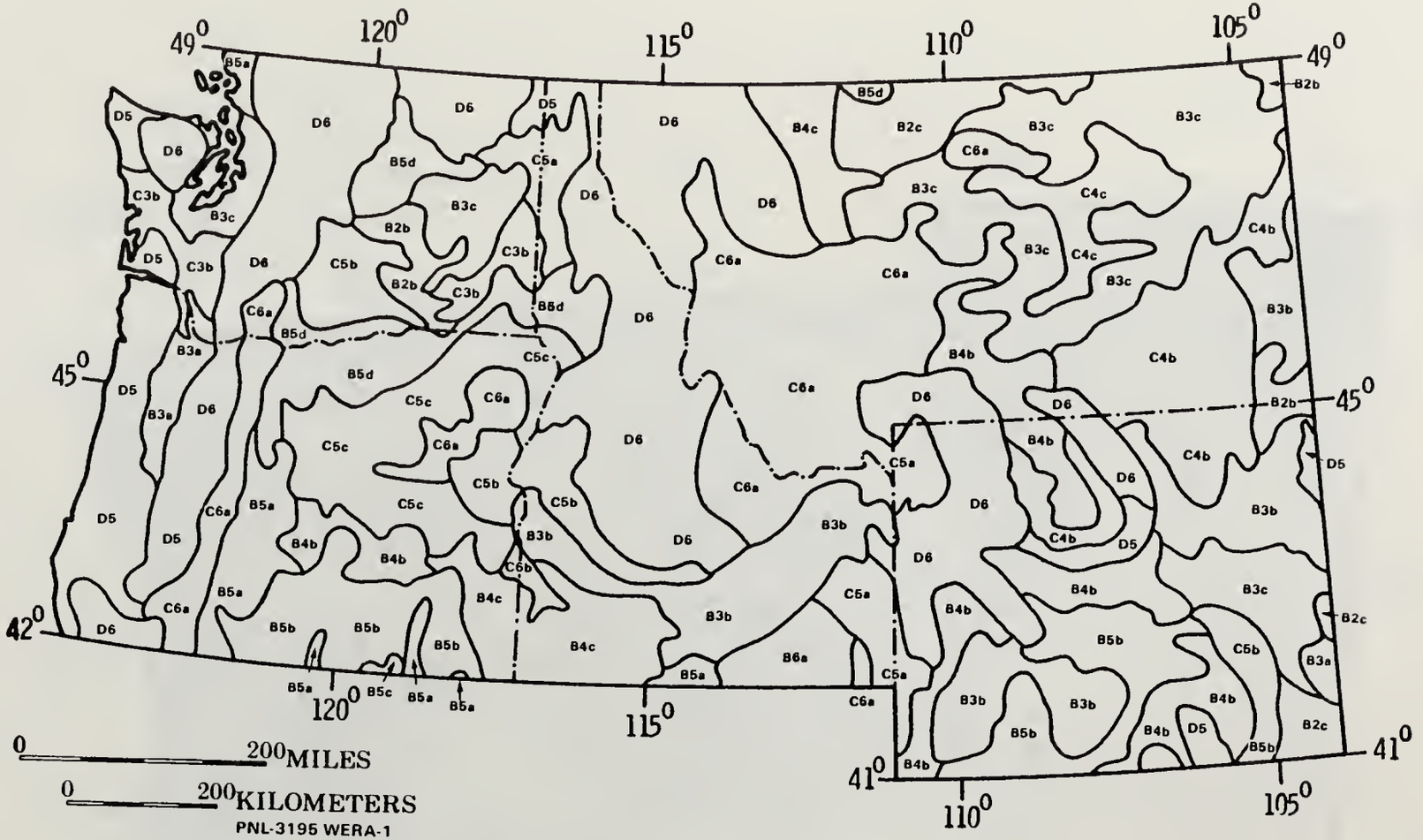


FIGURE 2.3. Classes of Land-Surface Form in the Northwest

LEGENO

PLAINS

A1	FLAT PLAINS
A2	SMOOTH PLAINS
B1	IRREGULAR PLAINS, SLIGHT RELIEF
B2	IRREGULAR PLAINS

PLAINS WITH HILLS OR MOUNTAINS

A,B3a,b	PLAINS WITH HILLS
B4,a,b	PLAINS WITH HIGH HILLS
B5a,b	PLAINS WITH LOW MOUNTAINS
B6a,b	PLAINS WITH HIGH MOUNTAINS

OPEN HILLS ANO MOUNTAINS

C2	OPEN LOW HILLS
C3	OPEN HILLS
C4	OPEN HIGH HILLS
C5	OPEN LOW MOUNTAINS
C6	OPEN HIGH MOUNTAINS

HILLS ANO MOUNTAINS

O3	HILLS
O4	HIGH HILLS
D5	LOW MOUNTAINS
O6	HIGH MOUNTAINS

TABLELANOS

B3c,d	TABLELANOS, MODERATE RELIEF
B4c,d	TABLELANOS, CONSIDERABLE RELIEF
B5c,d	TABLELANOS, HIGH RELIEF
B6c,d	TABLELANOS, VERY HIGH RELIEF

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

A	>80% OF AREA GENTLY SLOPING
B	50-80% OF AREA GENTLY SLOPING
C	20-50% OF AREA GENTLY SLOPING
O	<20% OF AREA GENTLY SLOPING

LOCAL RELIEF (2nd LETTER)

1	0 TO 30m (1 TO 100 ft)
2	30 TO 90m (100 TO 300 ft)
3	90 TO 150m (300 TO 500 ft)
4	150 TO 300m (500 TO 1000 ft)
5	300 TO 900m (1000 TO 3000 ft)
6	900 TO 1500m (3000 TO 5000 ft)

PROFILE TYPE (3rd LETTER)

a	>75% OF GENTLE SLOPE IS IN LOWLANO
b	50-75% OF GENTLE SLOPE IS IN LOWLAND
c	50-75% OF GENTLE SLOPE IS ON UPLAND
d	>75% OF GENTLE SLOPE IS ON UPLAND

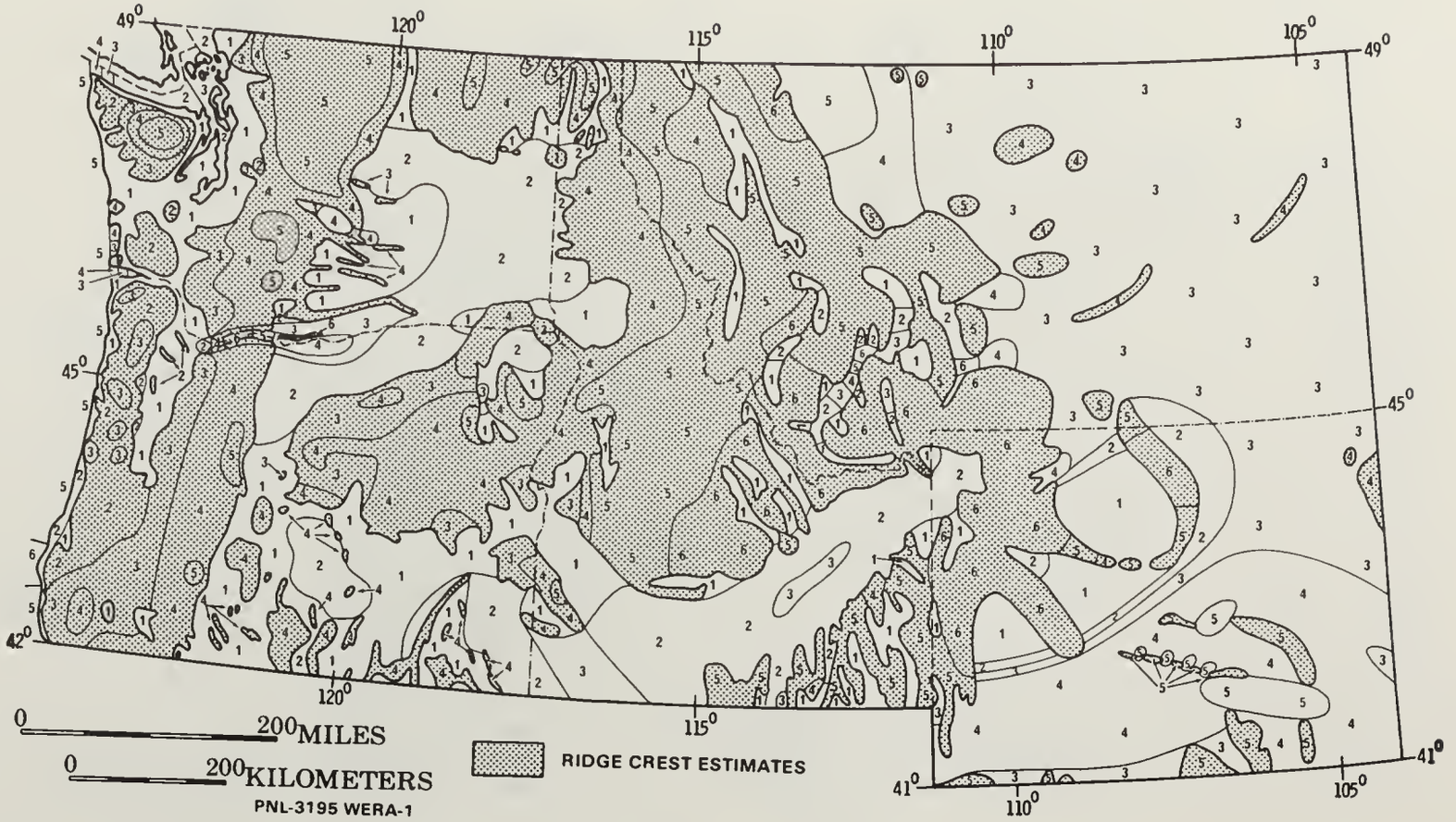


FIGURE 2.4. Annual Average Wind Power in the Northwest

TABLE 1.3. Classes of Wind Power Density at 10 m and 50 m[a]

Wind Power Class	10 m (33 ft) Wind Power Density, watts/m²	10 m (33 ft) Speed,[b] m/s (mph)	50 m (164 ft) Wind Power Density, watts/m²	50 m (164 ft) Speed,[b] m/s (mph)
	0	0	0	0
1	100	4.4 (9.8)	200	5.6 (12.5)
2	150	5.1 (11.5)	300	6.4 (14.3)
3	200	5.6 (12.5)	400	7.0 (15.7)
4	250	6.0 (13.4)	500	7.5 (16.8)
5	300	6.4 (14.3)	600	8.0 (17.9)
6	400	7.0 (15.7)	800	8.8 (19.7)
7	1000	9.4 (21.1)	2000	11.9 (26.6)

(a) Vertical extrapolation of wind speed based on the 1/7 power law.
(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 2.2. Areal Distribution of Wind Power Classes in the Northwest

Power Class	Land Area (km²) Equal or Exceeding Power Class: Northwest	Idaho	Montana	Oregon	Washington	Wyoming
1	1,300,000	220,000	380,000	250,000	180,000	250,000
2	420,000	52,000	160,000	40,000	39,000	120,000
3	300,000	18,000	150,000	12,000	10,000	110,000
4	120,000	6,100	29,000	7,800	4,900	77,000
5	31,000	3,900	15,000	460	800	11,000
6	6,000	800	2,500	27	38	2,700
7	200	0	0	0	0	200

Power Class	Percentage Land Area Equal or Exceeding Power Class: Northwest	Idaho	Montana	Oregon	Washington	Wyoming
1	100.	100.	100.	100.	100.	100.
2	33.	24.	43.	16.	22.	49.
3	24.	8.1	41.	4.8	5.8	42.
4	9.8	2.8	7.7	3.1	2.8	30.
5	2.4	1.8	3.9	0.18	0.45	4.4
6	0.47	0.37	0.65	0.01	0.02	1.1
7	0.02	0.00	0.00	0.00	0.00	0.08

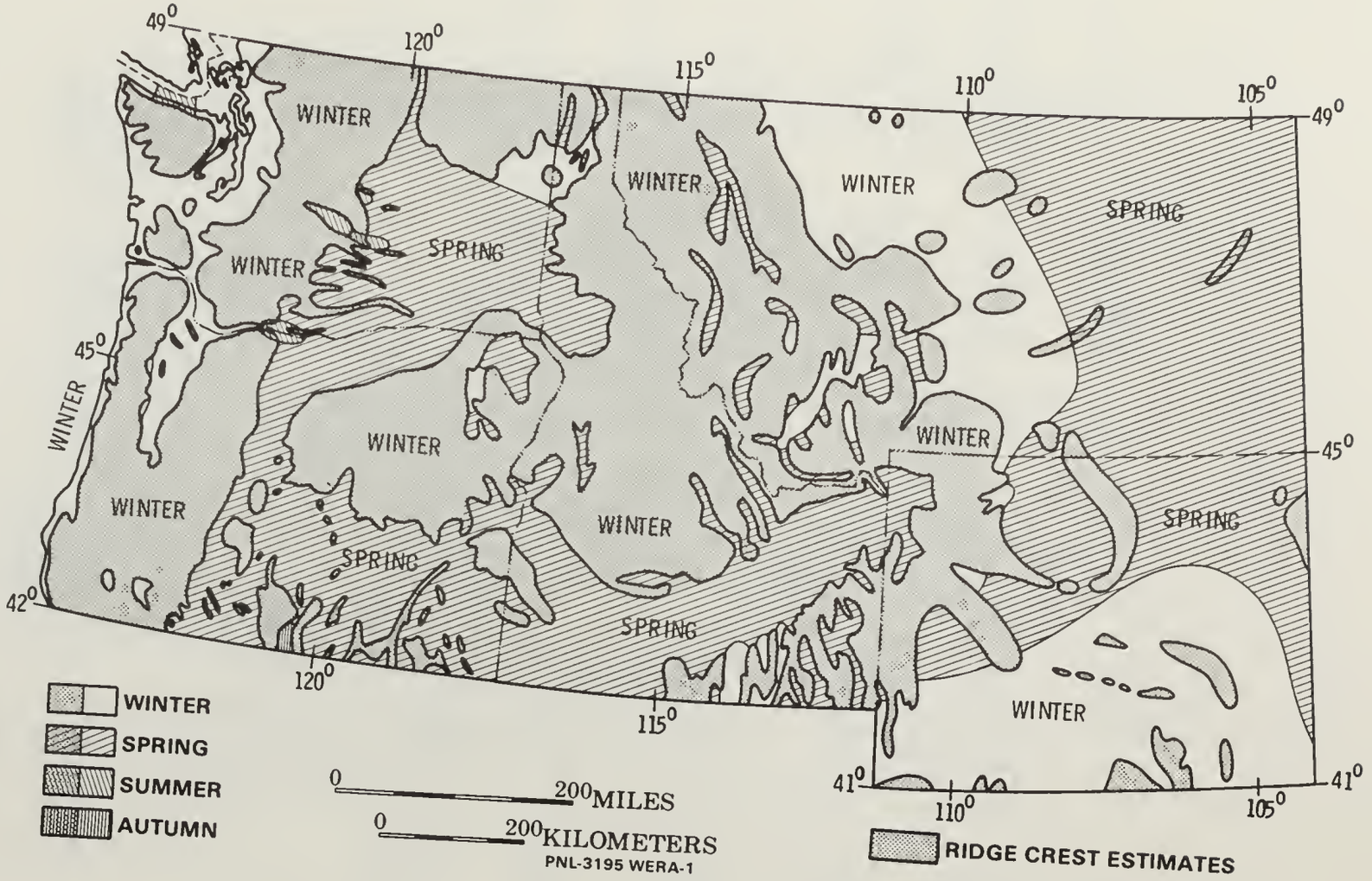


FIGURE 2.5. Seasonal Maximum Wind Power in the Northwest

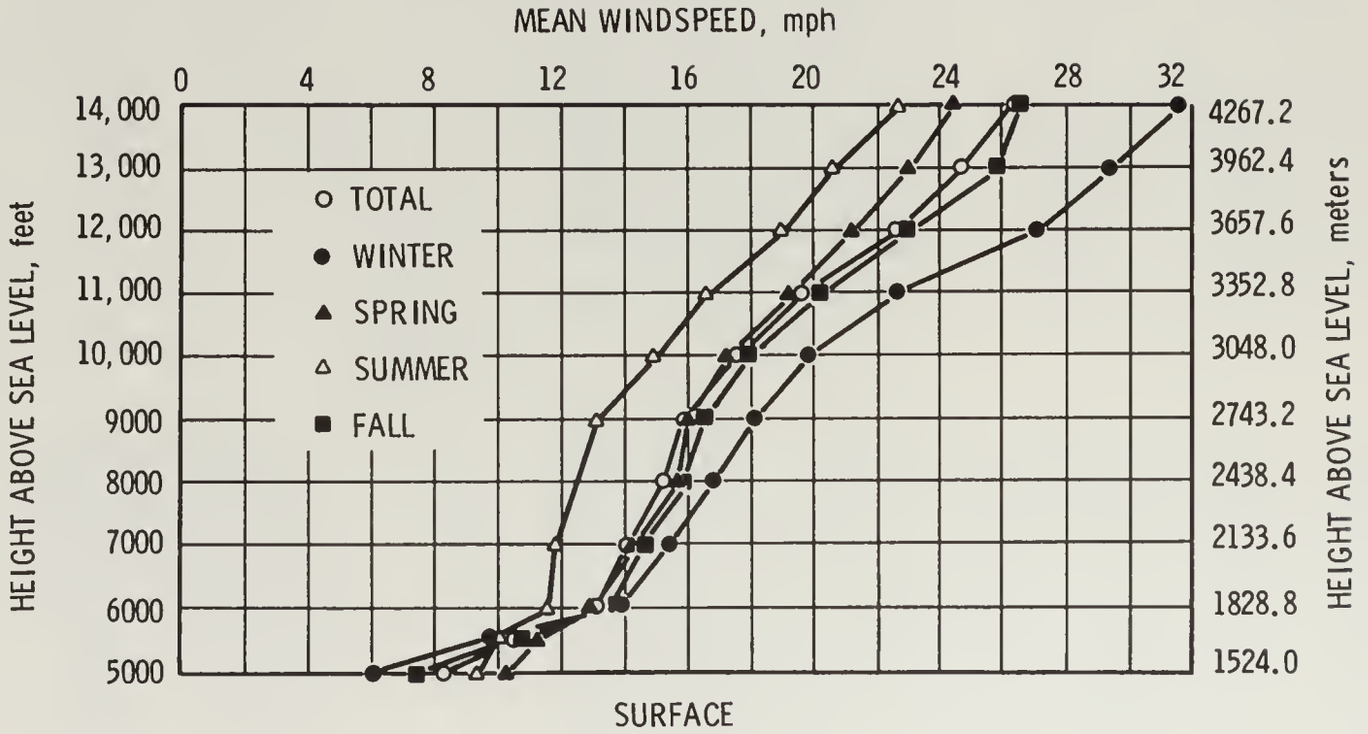


FIGURE 2.6. Annual and Seasonal Pibal Mean Wind Speed Profiles, Eastern Snake River Plain, Idaho (Yansky, Markee, Jr. and Richter 1966)

CHAPTER 3: STATE FEATURES

The wind resource for each state is described in Chapters 4 through 8. The text of each description is followed by maps, graphs and tables that identify features of the geography and the wind energy resource and summarize the data collected from the observation stations. The sequence of maps, tables and graphs used to depict these features is presented in Table 3.1. In the state descriptions, these illustrations are presented so that related information is on facing pages and can be viewed simultaneously.

To avoid repetition in the following chapters, the general format and content of the various maps, tables and graphs used to describe the wind resource for each state are summarized here.

3.1 MAPS OF STATE FEATURES

The maps of cultural geography show the locations of major cities, rivers and terrain features for each state. The maps of shaded topographic relief are reproductions of the 1:500,000 scale (except for Montana, which is 1:1,000,000) U.S. Geological Survey maps. The land-surface form maps are reconstructions of portions of the map of classes of land-surface form by Hammond (1964; this is also available at a scale of 1:17,000,000 on Plate 62 in the National Atlas of the United States). The use of the land-surface form map was described in Section 1.8.

Two maps are used to show the locations of stations with wind data. The first map gives the locations and names of the NCC stations with wind data in any form. The other map shows the locations of NCC, fire weather and other data stations that were utilized in this assessment of the wind resource.

The map of annual average wind power is accompanied by maps of the certainty rating of the estimated annual average wind power by grid cell, and of the areal distribution of the wind resource by grid cell. The certainty rating, which ranges from 1 (low) to 4 (high), indicates the level of confidence in the estimates of the wind resource in each cell of the grid. The certainty rating is based on the availability of wind data, the complexity of the terrain, and the inherent geographical variability of the wind resource (see Section 1.9). The maps of areal distribution give the percentage of land area in each cell estimated to experience an annual average wind power class equal to or exceeding power classes 2, 3, 4, and 5 (see Section 1.10).

Maps of the average wind power are presented for each season: winter (December, January, February); spring (March, April, May); summer (June, July, August); and autumn (September, October, November). The legend for the power classes is found with the annual average wind power map.

TABLE 3.1. Maps, Tables and Graphs Used to Depict the Wind Resource

Maps

Left Hand	Right Hand
Cultural Geography	Topographic Shaded Relief
Land-Surface Form	Legend to Land-Surface Form
NCC Station Locations	Location of Stations Used in Wind Assessment
Annual Average Wind Power	Legend to Wind Power Classes and Table on Areal Distribution
Certainty Rating	Legend for Certainty Rating
Areal Distribution (Power Classes 2 & 3)	Areal Distribution (Power Classes 4 & 5)
Seasonal Average Wind Power (Winter, Summer)	Seasonal Average Wind Power (Spring, Autumn)

Graphs

Summary Table of Selected Stations	Interannual Speed and Power
Monthly Speed and Power	Diurnal Speed
Directional Frequency	Speed Frequency
Speed Duration	Power Duration

3.2 FEATURES OF SELECTED STATIONS

The analysis of the wind resource on a state and regional basis depends on information from individual stations. For those stations with one- or three-hourly data on NCC magnetic tapes, a very detailed presentation of the temporal variation and character of the wind resource can be obtained. Graphs portraying various features of the wind resource have been prepared for selected stations in each state and are presented in the state chapters. For each station presented, a brief description of the station's topographical setting and unique features is given in the text preceding the maps and graphs. The geographical area represented by a station varies, depending on the complexity of the local terrain and variability of the wind resource.

A table listing the stations for which graphs and summaries of the features of the wind resource are presented precedes the series of graphs. Height adjustments were made only to obtain estimates of the average wind speed and power at 10 m and 50 m given in this table. No attempt was made to adjust to a reference height any of the other wind characteristics (e.g., diurnal wind speeds, frequency distributions of wind speed, wind direction, speed and power duration, etc.) presented in the graphs for selected stations. Caution should therefore be used in comparing and interpreting station plots.

On each station graph, the first line contains the station identification that corresponds to the name and location listed in the table and the month and year of the selected period of record. Only one period of record with constant anemometer height was plotted, even though some stations had several periods of record. Usually, periods when the anemometer was located on a mast directly on the ground were preferred to periods when the anemometer was located on the roof of a building.

The second line of each station graph contains the anemometer height (Z) in m and location, and the annual average wind speed (V) in m/s and wind power (P) in watts/m^2 at Z.

The coded information listed with the anemometer height is one of the following (Changery 1978):

R - indicates the anemometer was located on the roof of a control tower, operations building, hangar or other similar structure. Normal mast heights were 2 to 4 m (6 to 12 ft) above roof line; however, many inner-city locations used considerably taller masts. The listed height is elevation above ground level, not roof level; the "R" indicates an exposure type.

G - indicates the anemometer was located on a mast attached directly to the ground. Most anemometers at airport locations changed from a roof to ground exposure by the early 1960s.

B - indicates a beacon tower exposure. For these locations, neither R nor G was considered satisfactory.

UNK - indicates that documentation on instrument heights was not available.

If information on exposure was unavailable, no exposure code is given.

On a few station plots, an E follows the annual average wind power. If a pressure or temperature observation is missing, the wind power for that observation is computed using an air density based on station elevation. If the number of missing observations exceeds 25% of the total, then an E is used to designate that the wind power is an estimated value.

Up to 18 graphs of the same type may appear on one page to allow for station-to-station comparison. The scale of each set of plots was determined by the maximum range of values found for all stations in the region.

3.2.1 Interannual Wind Power and Speed

The plots of interannual wind speed and power portray the variations of the yearly average over the period of record. However, the year-to-year deviations from the long-term annual average may not be a reliable indicator of the deviations at nearby sites or areas (Elliott 1979b). For example, the interannual variations at Great Falls International Airport and Malmstrom Air Force Base for 1960 through 1964 show little apparent relation. A constant range of 300 watts/m^2 in wind power and 3 m/s in wind speed was used for all stations. Only yearly mean wind speeds based on 12 months' data (January through December) were plotted.

3.2.2 Monthly Average Wind Power and Speed

Graphs of the monthly average wind power and speed portray the monthly and seasonal trends of the wind. Stations with less than five years of observations may not show reliable seasonal trends. Also, stations in complex terrain may not represent the seasonal trends in nearby areas because of the influence of nearby terrain. Most of the station curves are within the 0 to 400 watts/m^2 range.

3.2.3 Diurnal Wind Speed by Season

The diurnal variation in wind speed according to season is plotted on graphs containing four curves, one for each season. Local standard time (LST) is used with hour 24 as midnight and hour 1 as the beginning hour. For National Weather Service and Federal Aviation Administration stations, the diurnal curves are based on 24 observations daily for periods ending before 1965, and on 8 observations daily for periods ending after 1964. For Air Force stations the diurnal curves are usually based on 24 observations daily regardless of the period. The diurnal curves for Navy stations are based on 24 observations daily for periods ending before March 1972 and on 8 observations for periods ending after February 1972.

3.2.4 Directional Frequency and Average Speed

Graphs of the annual average frequency of occurrence show the percentage of time that the observed wind direction was from each of 16-point compass sectors and the average wind speed of all observations in each sector. Some stations show a definite bias toward 8-point compass observations. The coincidence of peaks in the two curves indicates that the highest wind speeds occur from the prevailing directions. Caution should be used in applying these data to other sites, because nearby terrain and obstructions strongly influence the wind directions. Some of the directional data presented may not be reliable or representative because of the anemometer location.

3.2.5 Annual Average Wind Speed Frequency

Graphs of the annual average frequency of observed wind speeds are shown in 1 m/s intervals about each whole m/s wind speed. Along with the observed distribution, a Rayleigh wind speed distribution based on the annual mean speed is shown. Some of the stations show pronounced peaks in the observed distribution; these peaks reflect observer bias toward certain wind speeds, such as 2, 5, and 8 m/s (5, 10, and 15 knots). This bias occurs more frequently in records prior to 1960. Because many of the wind instruments used had a threshold velocity of about 1.5 m/s (3 knots), the frequency of observations in the 1 m/s class is often lower than the frequency of the calm and 2 m/s classes.

3.2.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in two sets of graphs. Abrupt changes in the slope of the duration curves for speed and power usually correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity. Points are plotted at 1 m/s intervals for the speed duration curves. Points are plotted every 50 watts/m^2 up to 500 watts/m^2 and every 100 watts/m^2 up to 1,000 watts/m^2 in the power duration curves.

IDAHO

CHAPTER 4: IDAHO

Idaho covers an area of 216,413 km^2 (83,557 mi^2) and had a population of 713,015 in 1970. Most of Idaho's residents live in the major cities of the Snake River plain in the south and near the Washington border in the north (see Figure 4.1). The largest cities are Boise and Pocatello in the Snake River plain.

Most of Idaho is mountainous (see Figure 4.2). Local relief exceeds 900 m (3,000 ft) in most of the mountainous region (see Figure 4.3); much of the rugged central part of the state, including the Clearwater and Salmon River Mountains, is a roadless wilderness area. The highest mountain summits are 2,700 to 3,700 m (9,000 to 12,000 ft) in the south and 1,800 to 2,500 m (6,000 to 8,000 ft) in the north.

Wind data are fairly abundant in the Snake River plain where the major towns and cities are located (Figure 4.4). Data are generally sparse for the tablelands in the southwestern corner of Idaho and the mountainous areas (Figure 4.5). Fire weather data are abundant in the mountainous regions, but only those stations for which more than 70% of the single daily observations during the fire season exceeded 3.5 m/s are used.

4.1 ANNUAL AVERAGE WIND POWER

The annual average wind power (Figure 4.6) is class 4 or higher on exposed ridge crests and mountain summits throughout the state. Class 3 wind power exists in the upland areas of the eastern Snake River plain and in the southwestern corner of the state. The prevailing strong winds are generally southwesterly in these areas.

Except for the area northwest of Mountain Home, the wind power over most of the Snake River plain is class 2. On the plain this class mostly refers to flat areas that are well exposed to the prevailing westerly-to-southwesterly winds. The summits of isolated hills and buttes in the Snake River plain, such as Big Southern Butte, may have considerably greater wind power (e.g., at least one or two classes higher) than the estimate for the plain.

The west end of the Snake River plain (from Mountain Home to the Oregon border) is sheltered from the prevailing strong southwesterly flow by the Owyhee Mountains and has lower wind energy (class 1) than the central and eastern Snake River plain. Wind energy is also class 1 in the mountain valleys and basins of southern Idaho, except for the corridors in the extreme south where moderate-to-strong winds frequently blow during the winter.

In northern Idaho, the annual average wind power is class 2 in the eastern fringe of the Palouse Hills north of Lewiston and in the Coeur d'Alene area. Class 1 is estimated for the basin area east of Lewiston and sheltered valleys in the panhandle.

4.1.1 Certainty Rating of the Wind Resource

The wind power estimates for most of the Snake River plain have certainty ratings of 3 or 4 (see Figure 4.7) because of the availability of existing data and the low complexity of the terrain (plains with low hills). However, two areas in southern Idaho are assigned a certainty rating of only 1. These are the tablelands in the southwestern corner of Idaho where no year-round data exist and the corridor north of Strevell in southeastern Idaho where a large spatial variability of the resource is anticipated.

In northern Idaho, the Lewiston area wind power has a certainty rating of 4, while the tablelands east of Lewiston have a rating of 3. Except for the Coeur d'Alene area, the broad valleys of northern Idaho are given a certainty rating of only 2 because of the limited data and uncertain variability of the resource.

Although no year-round data were available from exposed sites in mountainous terrain, the mountain summit and ridge crest estimates are given a certainty rating of 2 because upper-air wind data were used to approximate the power in these areas.

4.1.2 Areal Distribution

The areal distribution of wind power in Idaho is illustrated in Figure 4.8. The numbers identify the percentage of area in each cell of the grid in which the wind power equals or exceeds some threshold value. Although class 4 and higher wind power is predicted in 62% of the grid cells, only about 3% of the land area is estimated to experience these power densities (see Table 4.1). This is because a low percentage of land area in mountainous terrain has the map value of wind power. The maps of areal distribution are rather featureless for wind power class 4 or higher; values of 2, 5, and 10% represent ridge crest and mountain summit estimates. However, large areas of class 3 power are associated with upland portions of the eastern Snake River plain and the tablelands south of the Owyhee Mountains. Virtually every grid cell in the state has a significant fraction (20 to 100%) of area with only class 1 wind power because of local sheltering by the surrounding higher terrain.

4.2 SEASONAL WIND POWER

Wind power maps for each season are shown in Figure 4.9. The season of maximum wind power is generally spring over most of the plains, basins, and valleys and winter over mountain summits and ridge crests. Summer is the season of lowest wind power throughout most of the state.

4.2.1 Winter

During the winter, wind power is estimated to be exceptionally high (classes 6 and 7) on exposed mountain summits and ridge crests throughout Idaho; however, winters at these high elevations are often severe, with heavy snow and icing. Class 3 power and above may occur in some of the valley corridors in southeastern Idaho, where strong winds frequently blow from the Great Salt Lake basin of Utah into the Snake River plain. The wintertime wind characteristics for these valley corridors are evident from the data for Strevell and Pocatello, which show a winter maximum of class 3 or higher. Strong winds are not evident or expected in the valleys of extreme southeastern Idaho, where the mountainous region covers a more extensive area and no distinct corridors are apparent. Class 3 wind power is also estimated for the upland area of the southwestern corner of the state.

Even though the winds aloft are strongest during the winter season and are predominantly westerly, the winter wind power is only class 1 or 2 in the Snake River plain because of the effects of air stability on the wind profile. Valleys and basins in the mountainous areas throughout the state are also estimated to have only class 1 or 2 wind energy except for the corridors in the extreme south.

4.2.2 Spring

In the spring, exposed ridge crests in all mountainous areas of the state are estimated to have class 4 and 5 wind power. The Snake River plain, from Mountain Home east to Idaho Falls, and the upland area of southwestern Idaho have class 3 wind power potential. Prevailing strong winds over these areas are usually west to southwest during the spring, which is the season of maximum wind power in the Snake River plain. Wind power in the eastern and western ends of the Snake River plain is class 2 because of topographic shielding. Strong wind corridors that were present in the extreme southern part of Idaho in winter are no longer present in the spring. Although spring is the season of highest wind power throughout most of the broad valleys and basins in Idaho, the wind power is not expected to exceed class 2. The class 3 area in northern Idaho, in the vicinity of Moscow, represents hilltops in the eastern fringe of the Palouse Hills.

4.2.3 Summer

In the summer, wind power is only class 1 and 2 over the entire state, except for some of the highest mountain summits and ridge crests. The upland areas of the Snake River plain and the southwestern corner appear to have the most favorable summer wind energy.

4.2.4 Autumn

In autumn, wind power over mountainous areas generally increases from September to November as the upper-air wind speeds intensify. Over the plains and basins, however, the increase in the upper-air winds is not felt at the surface because of a decrease in vertical mixing of the air that accompanies the decline in solar radiation in autumn. The average upper-air wind speeds for autumn and spring are not significantly different. However, the vertical mixing and average wind power in the Snake River plain and other valleys and basins are less in autumn than in spring. The class 2 areas in the valleys in southeastern Idaho are the areas where frequently strong corridor winds begin in late autumn and continue through the winter months.

4.3 FEATURES OF SELECTED STATIONS

Table 4.2 gives the location and annual wind speed and power density of eleven stations in Idaho. Graphs of other features of the wind resource at these stations are shown in Figures 4.10 to 4.16. Eight of these are in the Snake River plain, which extends from Boise in the west across to Idaho Falls and Dubois in the east.

Boise Airport appears to be representative of the west end of the Snake River plain from Mountain Home northwest to the Oregon border.

Burley Airport, situated along the Snake River in the central part of the Snake River plain, has moderately good exposure to the prevailing westerly winds.

Dubois is located in the northeastern part of the Snake River plain, which rises in elevation north of Dubois. As a result, the station frequently experiences light northerly drainage winds.

Gooding Airport, located in the Snake River plain, appears to be well exposed; however, the anemometer height is unknown for the period of record.

Idaho Falls has three stations for which the wind characteristics are known: Fanning Field and two sites on the National Reactor Testing Station (NRTS). One NRTS site, located 67 km (42 mi) northwest of Idaho Falls, is in a shallow basin and has the least wind power of the three. The other two stations appear to be fairly representative of the plains in this part of Idaho.

Malad City is in a sheltered valley in the mountainous terrain of southeastern Idaho.

The Mullan Pass station, located in the Bitterroot Range in northern Idaho, is on a ridge near Mullan Pass. However, the winds at this site do not represent an exposed ridge crest site because of the anemometer location (Changery 1978). In spite of this problem, Mullan Pass is included to examine the seasonal and diurnal trends at a ridge crest site, even though the magnitude of the wind resource is less than that expected at an exposed location.

Pocatello Airport, located in the Snake River plain, has winds that are strongly influenced by the long valley corridor south of the airport. The city of Pocatello is sheltered by local topography and is estimated to have significantly lighter winds than the airport.

Strevell is situated in a low gap in a mountain range near the Utah border. This gap serves as a wind corridor, connecting the Snake River plain and Great Salt Lake basin of Utah.

4.3.1 Interannual Wind Power and Speed

Only two stations, Boise and Pocatello, have selected periods of record of 10 years or more during which the anemometer was not moved. However, the interannual variations at these two stations do not coincide (Figure 4.10). For example, 1970 was a low wind speed year at Pocatello and a high wind speed year at Boise, relative to the long-term averages at these stations. The ratios of the highest annual wind power to the lowest annual wind power are 1.7 for Boise and 1.9 for Pocatello. Mullan Pass shows the largest interannual variation in wind power, a ratio of 2.5 between the highest and lowest annual wind power.

4.3.2 Monthly Average Wind Power and Speed

Except for Pocatello, all stations in the Snake River plain show maximum wind energy during the spring. However, at sites located near the mountains along the edge of the Snake River plain, effects of local terrain can alter the monthly wind energy trends (Figure 4.11). For example, the Pocatello Airport, located near the mouth of a long north- to south-oriented valley corridor, has slightly higher average wind power in winter (152 watts/m^2) than in spring (131 watts/m^2). During the winter, the direction of highest average wind speed is south to south-southeast while in spring it is west-southwest. Apparently, the winter maximum is associated with the influence of the long valley corridor. Moreover, Pocatello Airport is located far enough out in the plain so that it has good exposure to the prevailing westerly winds. The city of Pocatello, which is located only 10 to 15 km (6 to 9 m) southeast of the airport, appears sheltered from both the strong southerly winds and westerly-to-southwesterly winds. Thus, the Pocatello Airport may not be very representative of the wind characteristics in or near Pocatello.

Strevell has a distinct winter maximum and should be representative of other gaps and corridors in that area which connect the Snake River plain and Great Salt Lake basin. The winds are channeled and enhanced through these corridors and are strongest during the winter. However, Malad City, located about 80 km (50 mi) east-northeast of Strevell, is in a sheltered valley and has minimum wind energy in the winter, an almost opposite monthly trend from that of Strevell. This seasonal trend is characteristic of most sheltered valleys in Idaho. Winds are generally light throughout the year and frequently calm during winter, when strong thermal stability and topographic shielding prevent the strong winds aloft from reaching the valley bottom. Changery (1978) reports the wind speeds at Malad City to be unrepresentative of this area during the period of record. Nevertheless, the seasonal trend indicates that this site is in a sheltered valley and not in a windy corridor. This station was included to further evaluate and understand the nature of the geographical and seasonal variability of wind energy in southeastern Idaho.

4.3.3 Diurnal Wind Speed by Season

Stations in the Snake River plain generally have the highest wind speeds during the afternoon and early evening hours, 1200 to 1900 local standard time (LST) (Figure 4.12). The peak winds appear to occur between 1500 and 1800 LST during the spring and summer and around 1500 LST during winter. The greatest diurnal variations generally occur in summer and the least in the winter. During the winter, Dubois has slightly higher wind speeds at night than during the day, probably because of the nighttime drainage winds. Mullan Pass, a ridge crest site, has very little diurnal variation throughout the year and on the average, wind speeds appear just slightly greater during the night.

4.3.4 Directional Frequency and Average Speed

The directional frequency (Figure 4.13) of the prevailing winds at stations in the Snake River plain appears to be primarily influenced by the orientation of the plain with respect to the mountains. The prevailing winds are southeast and northwest at Boise, east and west at Gooding, west-southwest and south at Burley, southwest and north at Idaho Falls, and north-northeast and south-southwest at Dubois. In the central and eastern parts of the plain, the strongest winds are generally from the west to south-southwest.

4.3.5 Annual Average Wind Speed Frequency Distribution

Because observer bias and low instrument threshold speeds so distort the observed frequency distribution (Figure 4.14), the representativeness of the Rayleigh speed distribution is hard to evaluate. Observer biases are readily apparent in the frequency distributions for Gooding, Mullan Pass, and Strevell, which have periods of record in the 1940s and 50s. Burley, Dubois, Idaho Falls (Fanning Field), and Malad City also indicate some observer bias.

4.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 4.15 and 4.16. Abrupt changes in the slope of the duration curves correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

FIGURE 4.1. Geographic Map of Idaho

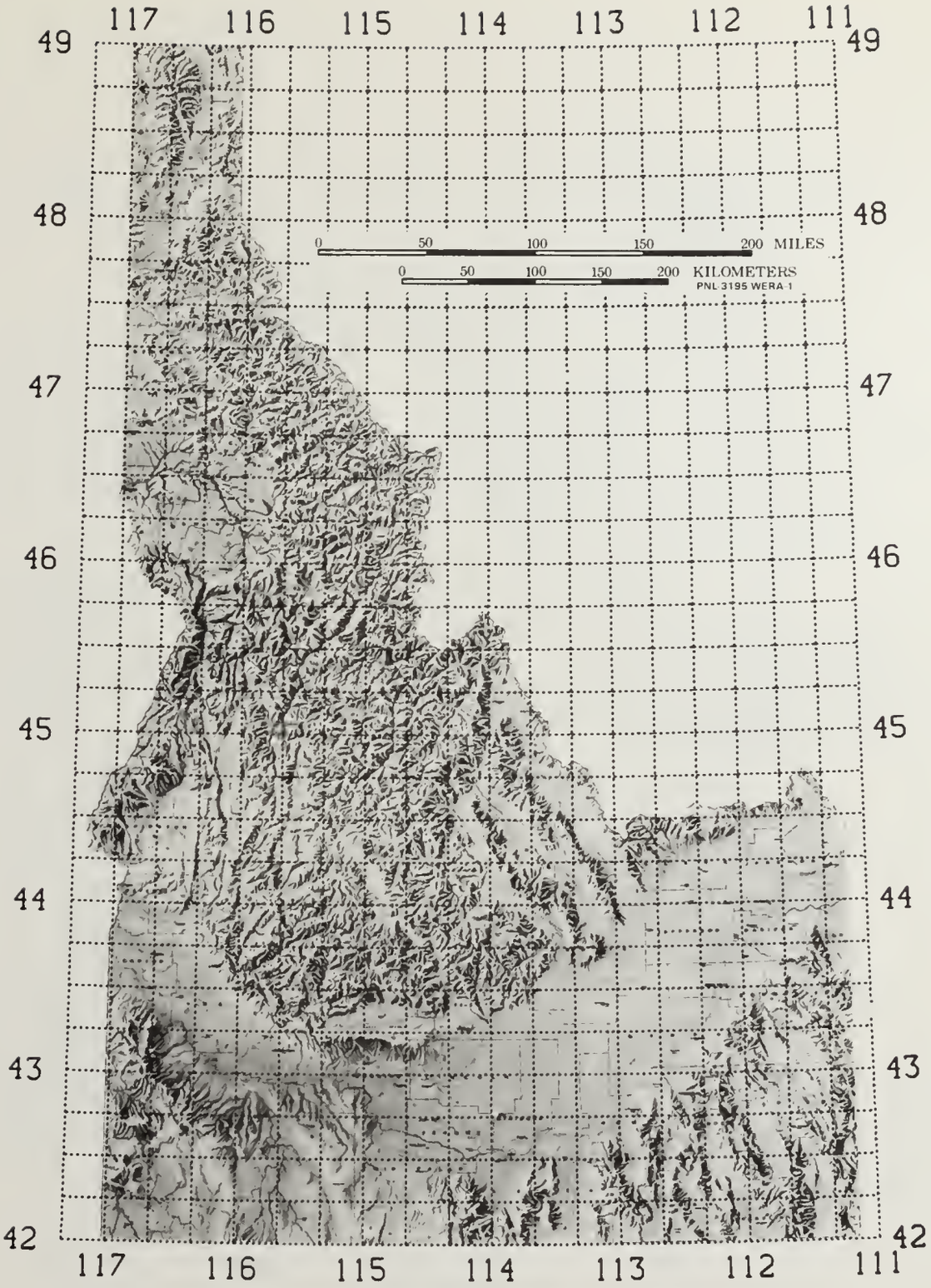


FIGURE 4.2. Topographic Map of Idaho

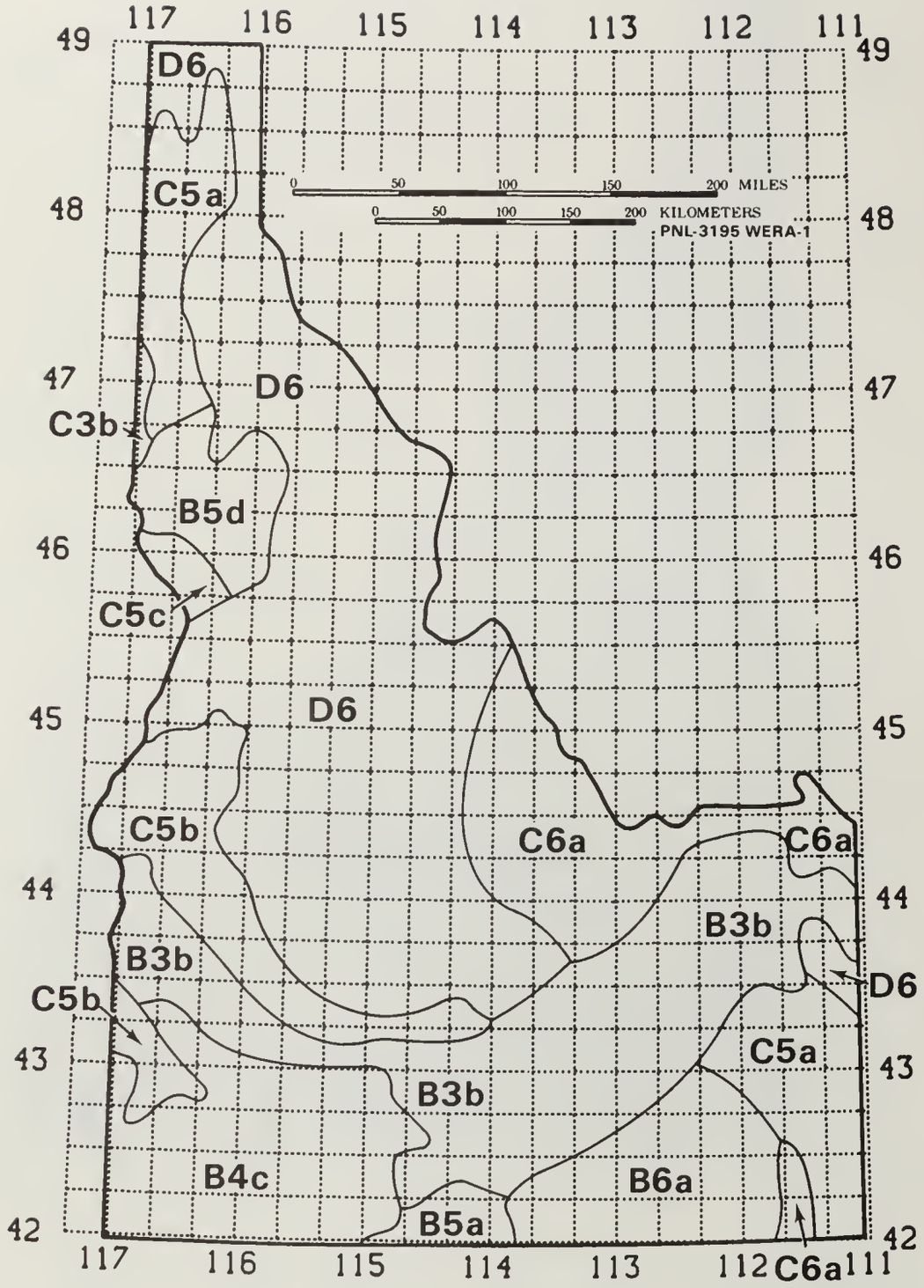


FIGURE 4.3. Land-Surface Form Map for Idaho

LAND-SURFACE FORM LEGEND

PLAINS

A1	FLAT PLAINS
A2	SMOOTH PLAINS
B1	IRREGULAR PLAINS, SLIGHT RELIEF
B2	IRREGULAR PLAINS

PLAINS WITH HILLS OR MOUNTAINS

A,B3a,b	PLAINS WITH HILLS
B4,a,b	PLAINS WITH HIGH HILLS
B5a,b	PLAINS WITH LOW MOUNTAINS
B6a,b	PLAINS WITH HIGH MOUNTAINS

OPEN HILLS AND MOUNTAINS

C2	OPEN LOW HILLS
C3	OPEN HILLS
C4	OPEN HIGH HILLS
C5	OPEN LOW MOUNTAINS
C6	OPEN HIGH MOUNTAINS

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

TABLELANDS

B3c,d	TABLELANDS, MODERATE RELIEF
B4c,d	TABLELANDS, CONSIDERABLE RELIEF
B5c,d	TABLELANDS, HIGH RELIEF
B6c,d	TABLELANDS, VERY HIGH RELIEF

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

A	>80% OF AREA GENTLY SLOPING
B	50-80% OF AREA GENTLY SLOPING
C	20-50% OF AREA GENTLY SLOPING
D	<20% OF AREA GENTLY SLOPING

LOCAL RELIEF (2nd LETTER)

1	0 TO 30m (1 TO 100 ft)
2	30 TO 90m (100 TO 300 ft)
3	90 TO 150m (300 TO 500 ft)
4	150 TO 300m (500 TO 1000 ft)
5	300 TO 900m (1000 TO 3000 ft)
6	900 TO 1500m (3000 TO 5000 ft)

PROFILE TYPE (3rd LETTER)

a	>75% OF GENTLE SLOPE IS IN LOWLAND
b	50-75% OF GENTLE SLOPE IS IN LOWLAND
c	50-75% OF GENTLE SLOPE IS ON UPLAND
d	>75% OF GENTLE SLOPE IS ON UPLAND

FIGURE 4.4. NCC Station Locations in Idaho

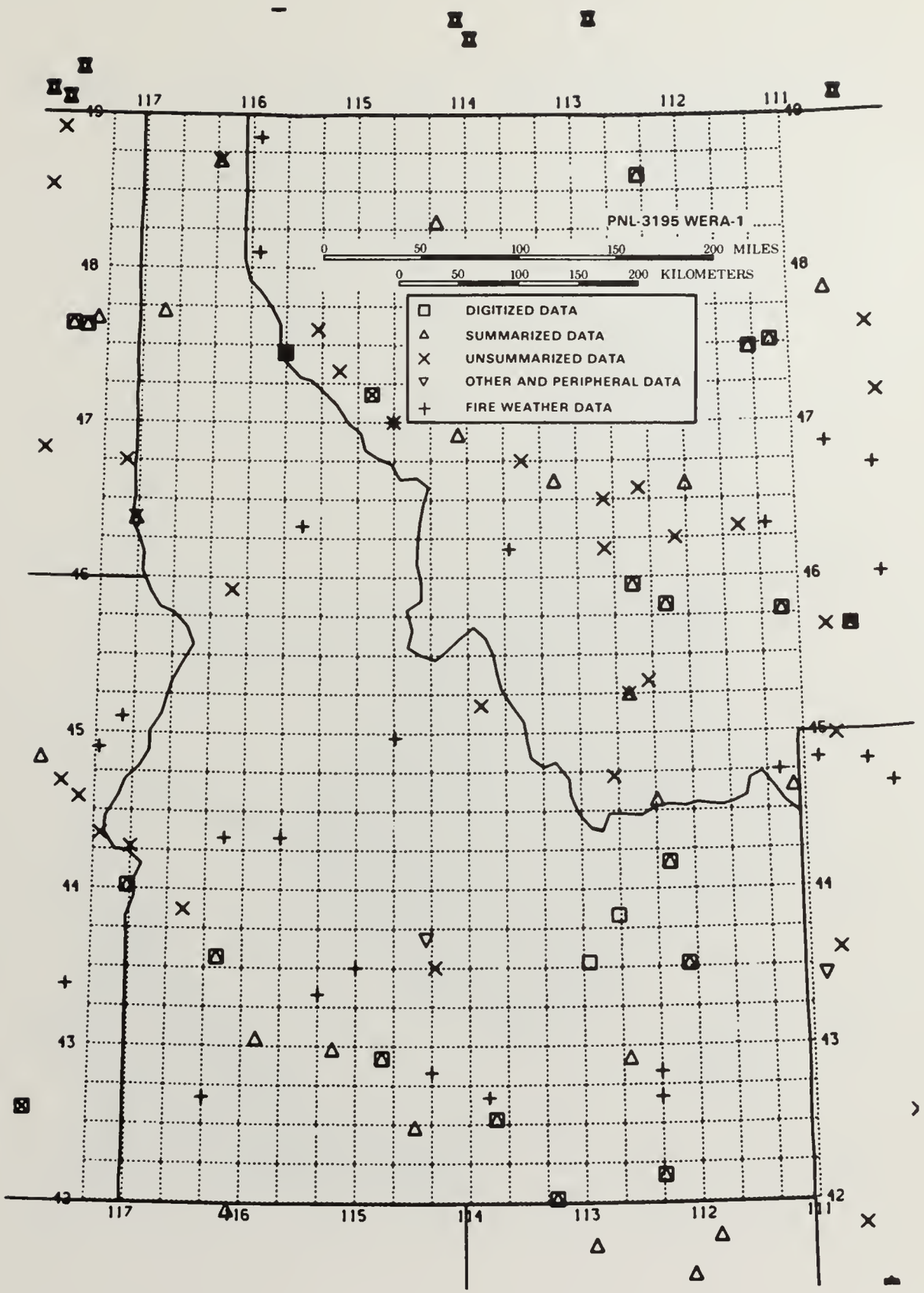


FIGURE 4.5. Location of Stations Used in Idaho Wind Assessment

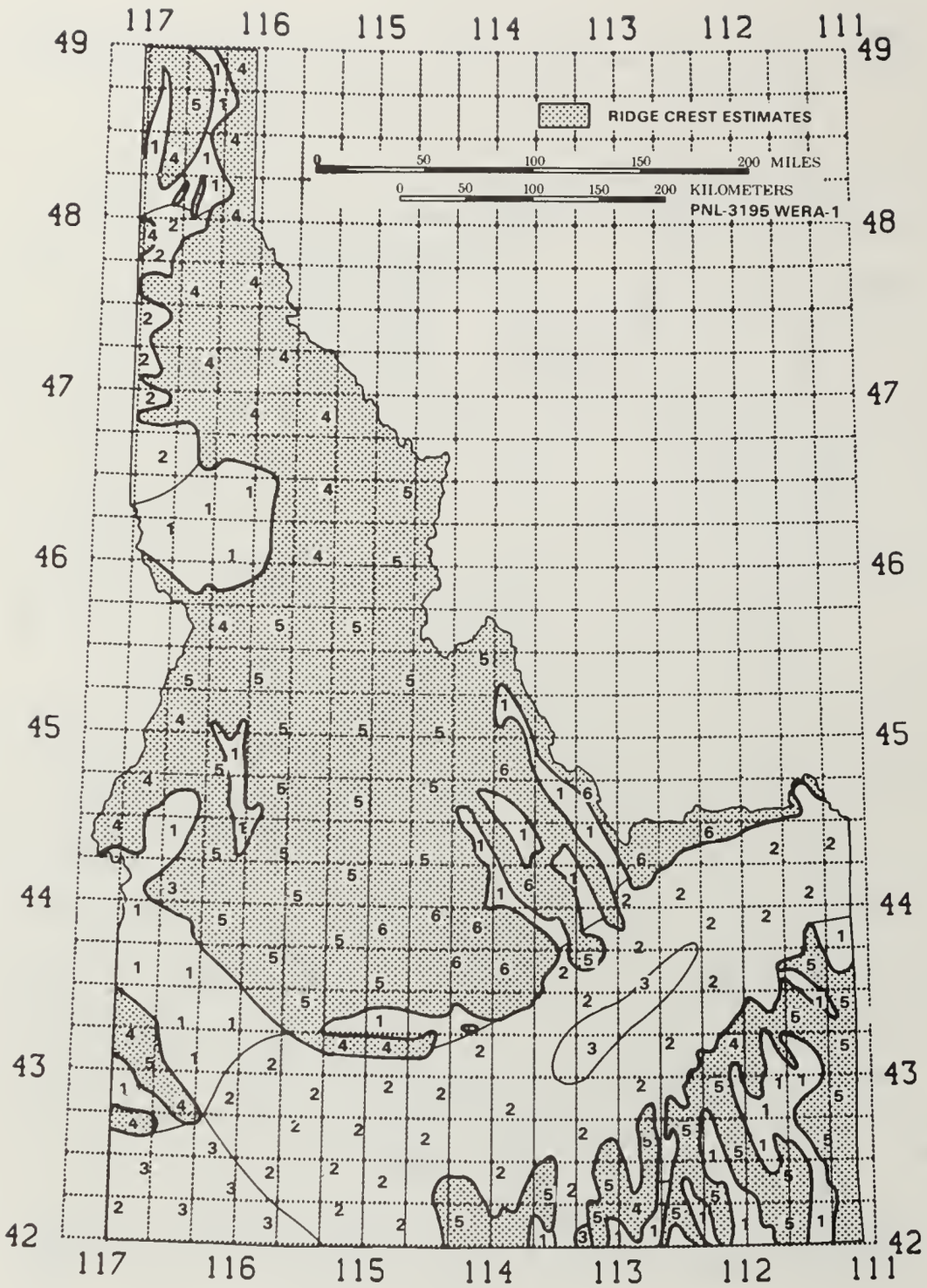


FIGURE 4.6. Idaho Annual Average Wind Power

Classes of Wind Power Density at 10 m and 50 m[a]

Wind Power Class	10 m (33 ft) Wind Power Density, watts/m²	10 m (33 ft) Speed,[b] m/s (mph)	50 m (164 ft) Wind Power Density, watts/m²	50 m (164 ft) Speed,[b] m/s (mph)
	0	0	0	0
1	100	4.4 (9.8)	200	5.6 (12.5)
2	150	5.1 (11.5)	300	6.4 (14.3)
3	200	5.6 (12.5)	400	7.0 (15.7)
4	250	6.0 (13.4)	500	7.5 (16.8)
5	300	6.4 (14.3)	600	8.0 (17.9)
6	400	7.0 (15.7)	800	8.8 (19.7)
7	1000	9.4 (21.1)	2000	11.9 (26.6)

[a] Vertical extrapolation of wind speed based on the 1/7 power law.
[b] Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 4.1. Areal Distribution (km^2) of Wind Power Classes in Idaho

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	160,000	76.	220,000	100.
2	35,000	16.	52,000	24.
3	11,000	5.3	17,000	8.1
4	2,300	1.0	6,100	2.8
5	3,100	1.4	3,800	1.8
6	800	0.37	800	0.37
7	0	0.00	0	0.00

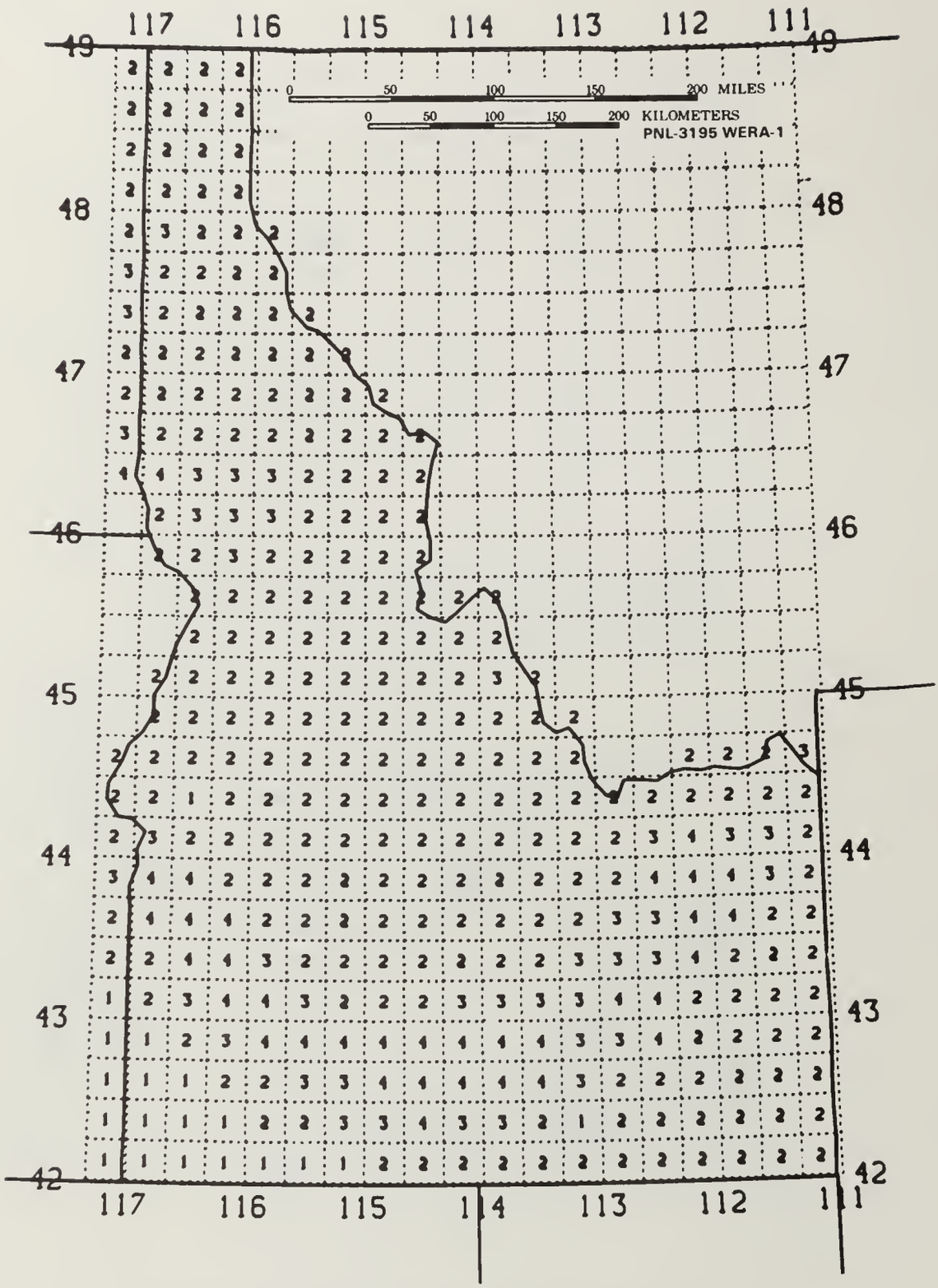


FIGURE 4.7. Certainty Rating of Idaho Wind Resource

CERTAINTY RATING LEGEND

Rating	Definition
1	The lowest degree of certainty. A combination of the following conditions exists: 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	A low-intermediate degree of certainty. One of the following conditions exists: 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	A high-intermediate degree of certainty. One of the following conditions exists: 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.

Class 2

Class 3

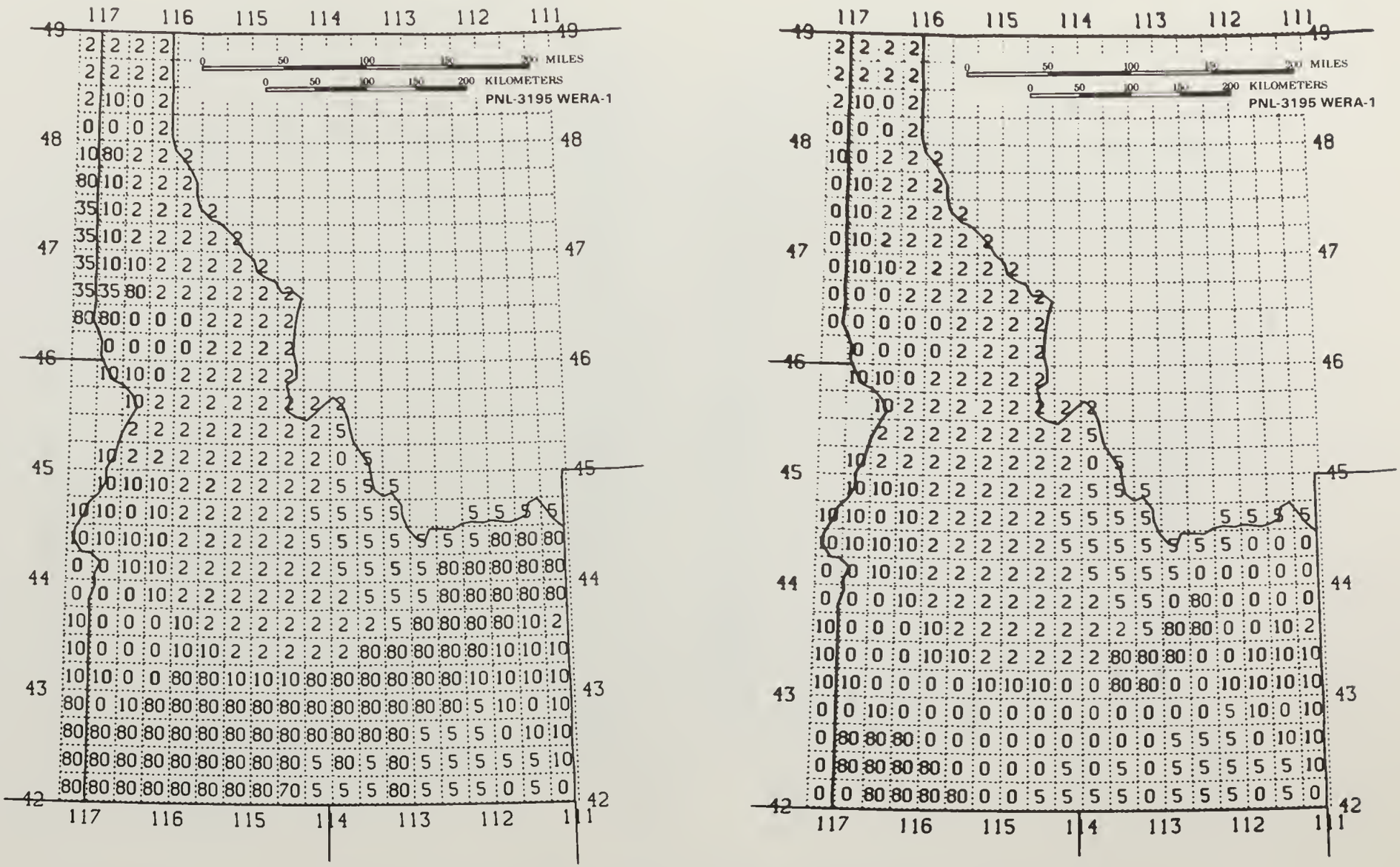
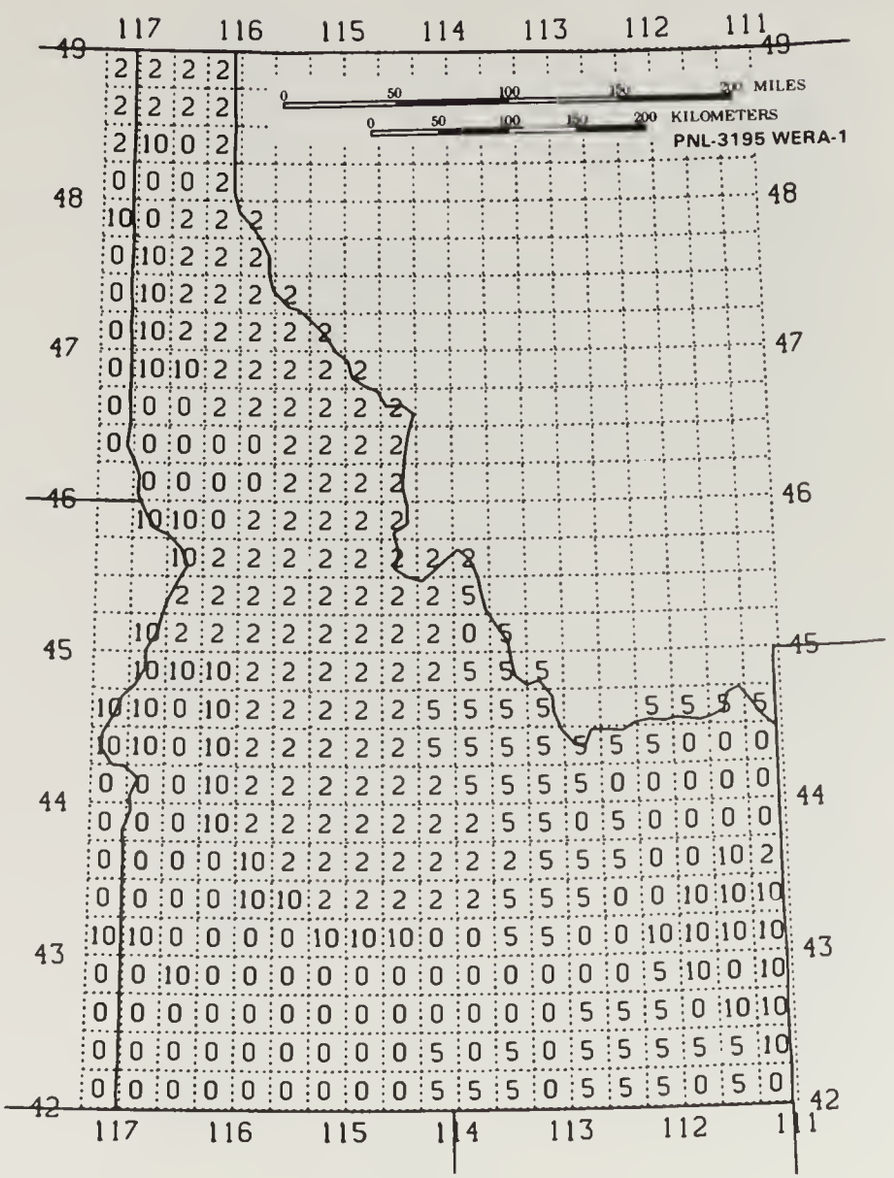


FIGURE 4.8. Areal Distribution of Wind Resource in Idaho (Power Classes 2 and 3); Percent of Land Area With or Exceeding Power Class Shown.

Class 4



Class 5

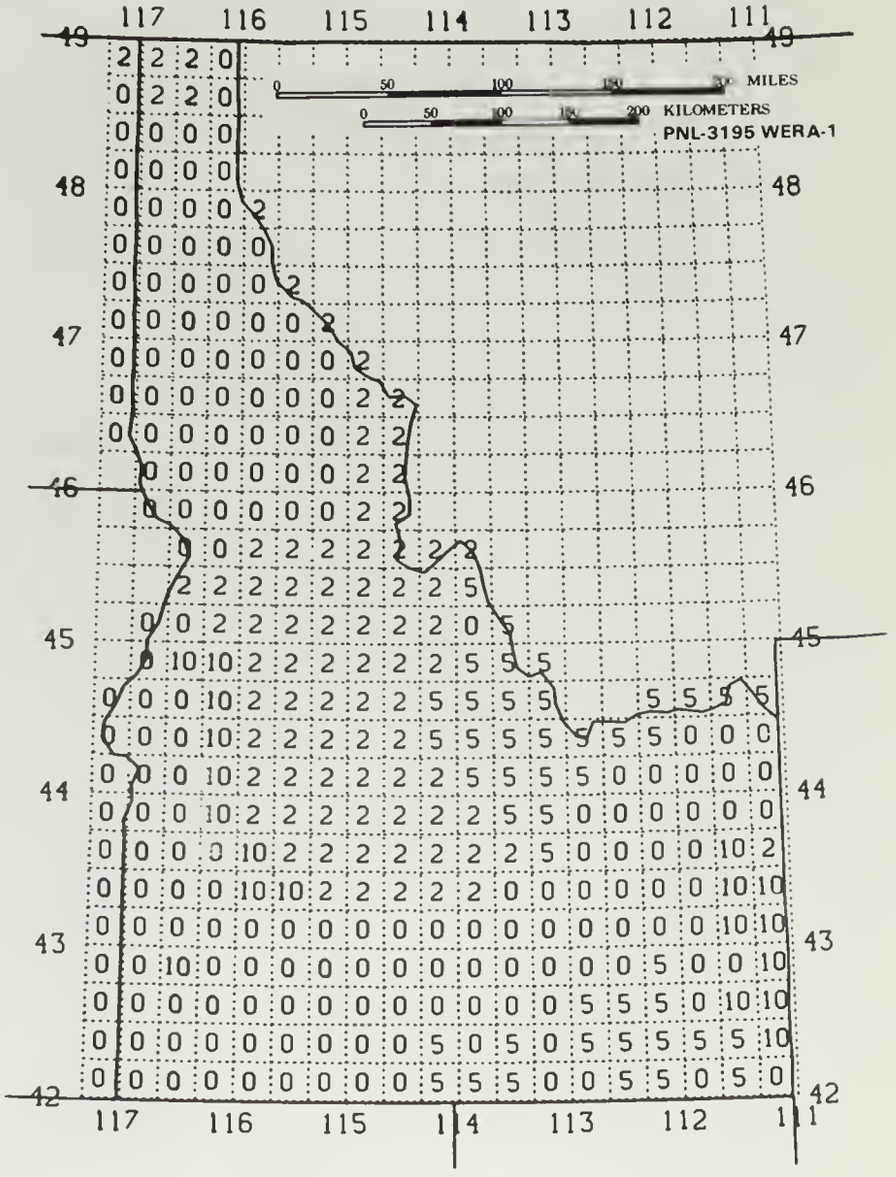


FIGURE 4.8 (Continued). Areal Distribution of Wind Resource in Idaho (Power Classes 4 and 5); Percent of Land Area With or Exceeding Power Class Shown.

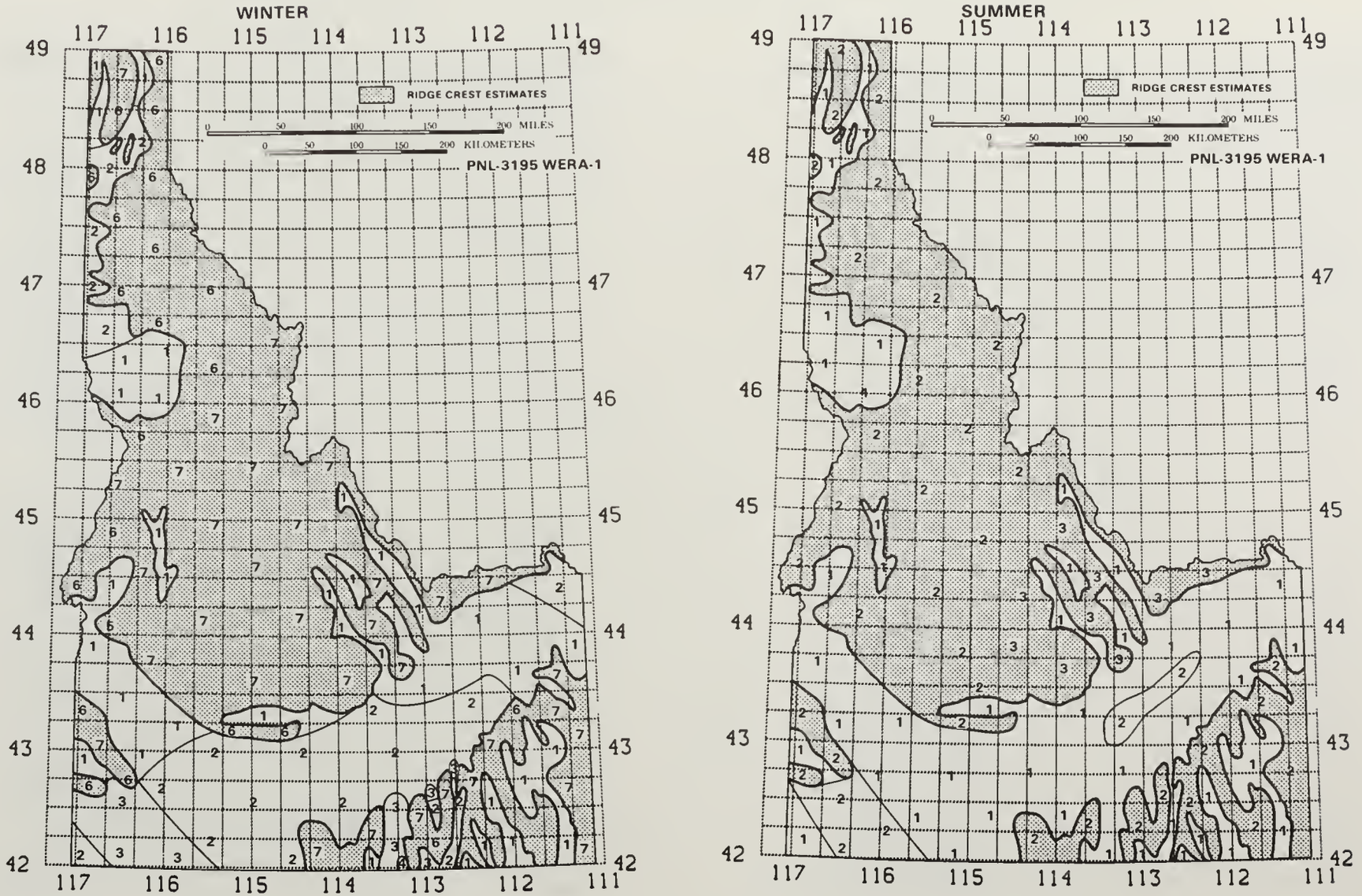


FIGURE 4.9. Seasonal Average Wind Power in Idaho (Winter, Summer)

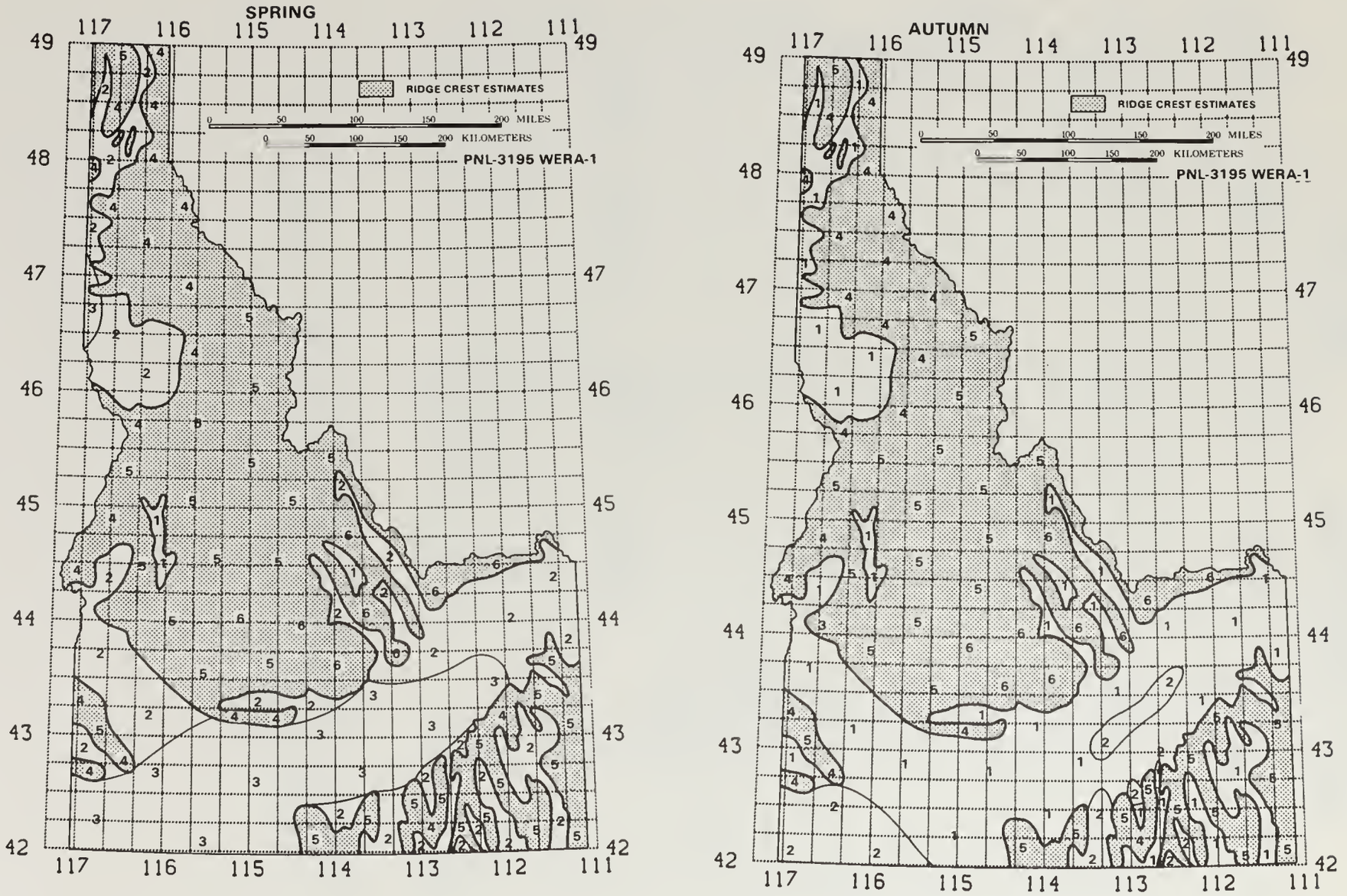


FIGURE 4.9 (Continued). Seasonal Average Wind Power for Idaho (Spring, Autumn)

TABLE 4.2. Idaho Stations with Graphs of the Wind Characteristics

Station	Station Name[a]	Latitude, Degrees North	Longitude, Degrees West	Elevation of Station, m	Period of Record, Month/Year	Anemometer Height, m	Annual Average Wind Speed, m/s: At Anemometer Height, m	At 10 m	At 50 m	Annual Average Wind Power, watts/m²: At Anemometer Height, m	At 10 m	At 50 m
Boise, Idaho	Boise Airport	43.57	116.22	876	08/58-12/76	6.1	3.9	4.2	5.3	67	83	165
Burley, Idaho	Burley Airport	42.53	113.77	1509	05/59-12/64	6.1	3.8	4.1	5.2	84	104	207
Dubois, Idaho	Dubois Airport	44.17	112.22	1563	09/50-12/54	6.7	3.5	3.7	4.7	67	80	158
Gooding, Idaho	Gooding Airport	42.92	114.77	1127	01/48-12/54	Unk[b]	4.6	4.6	5.8	111	111	221
Idaho Falls, Idaho	Idaho Falls Fanning Field	43.52	112.07	1448	03/60-12/64	6.1	4.1	4.4	5.5	92	114	227
Idaho Falls, Idaho	SPL, 67 km (42 mi) NW of Idaho Falls	43.83	112.68	1460	01/65-01/67	6.1	2.9	3.2	4.0	62	77	153
Idaho Falls, Idaho	SPL, 73 km (46 mi) W of Idaho Falls	43.53	112.95	1505	01/65-10/67	6.1	3.3	3.5	4.4	90	111	222
Malad City, Idaho	Malad City Airport	42.17	112.32	1363	01/48-12/54	Unk[b]	2.8	2.8	3.5	33	33	66
Mullan Pass, Idaho	Mullan Pass CAA	47.45	115.67	1840	01/48-12/54	8.8	4.3	4.4	5.5	90	95	189
Pocatello, Idaho	Pocatello Airport	42.92	112.60	1361	08/60-12/76	6.1	4.5	4.8	6.1	112	138	276
Strevell, Idaho	Strevell CAA	42.02	113.25	1617	01/48-12/50	6.7	4.8	5.1	6.4	118	150	300

[a]SPL-Special Purpose Office; CAA-Civil Aeronautics Administration Facility.
[b]Unk - Anemometer height is unknown. Height of 10 m was assumed for estimating wind speed and power at 10 and 50 m.

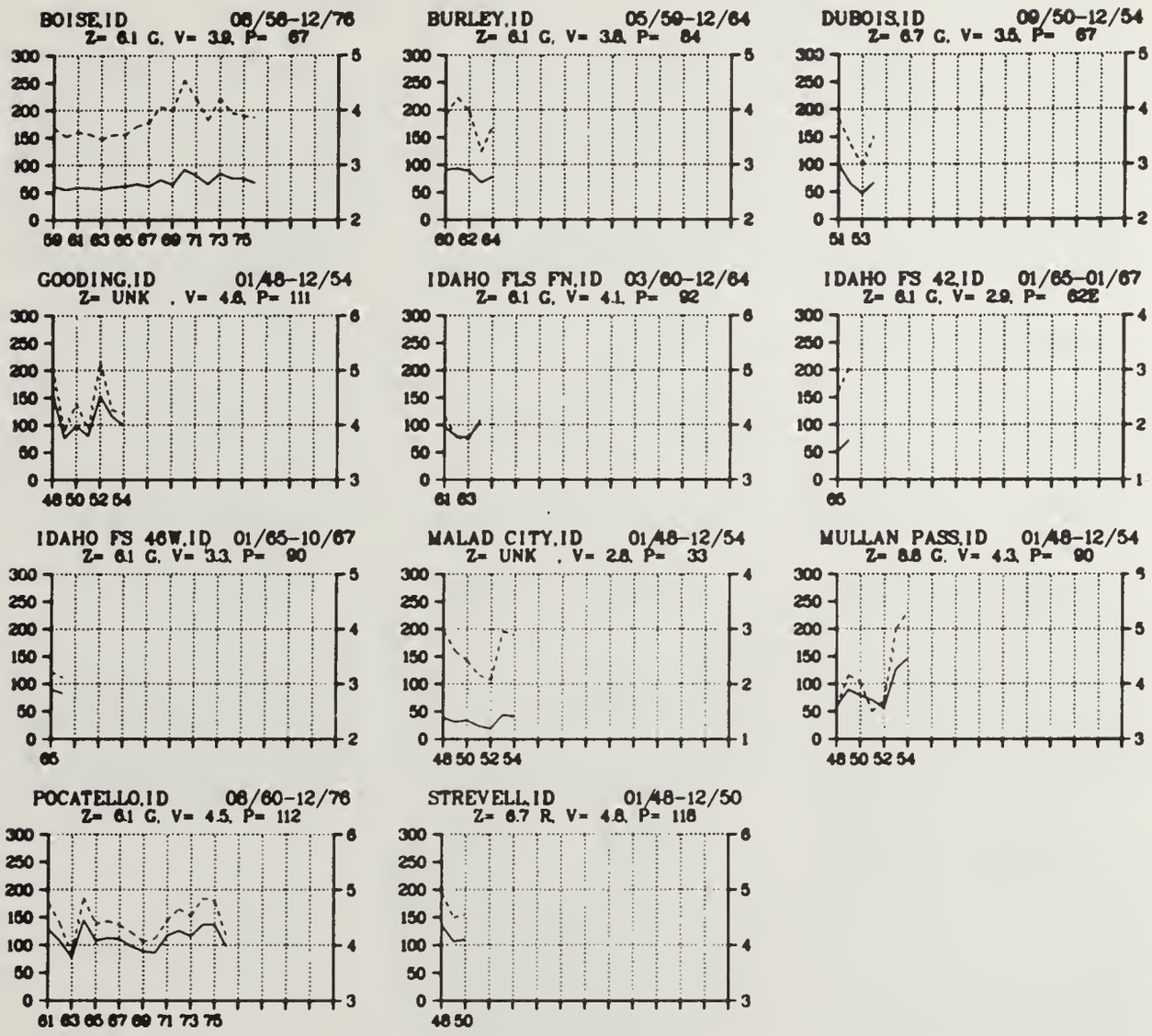


FIGURE 4.10. Interannual Wind Power and Speed for Idaho

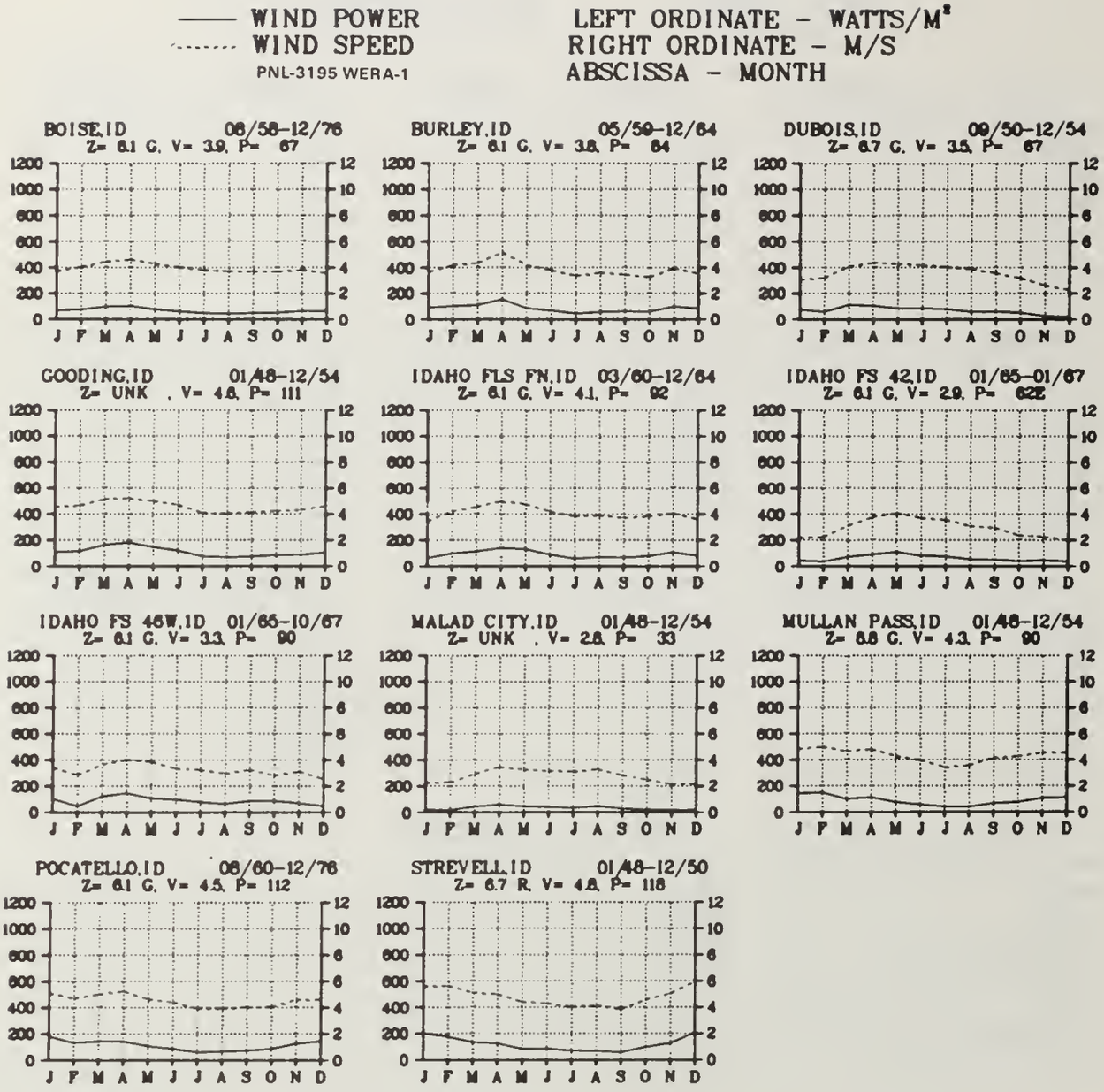


FIGURE 4.11. Monthly Average Wind Power and Speed for Idaho

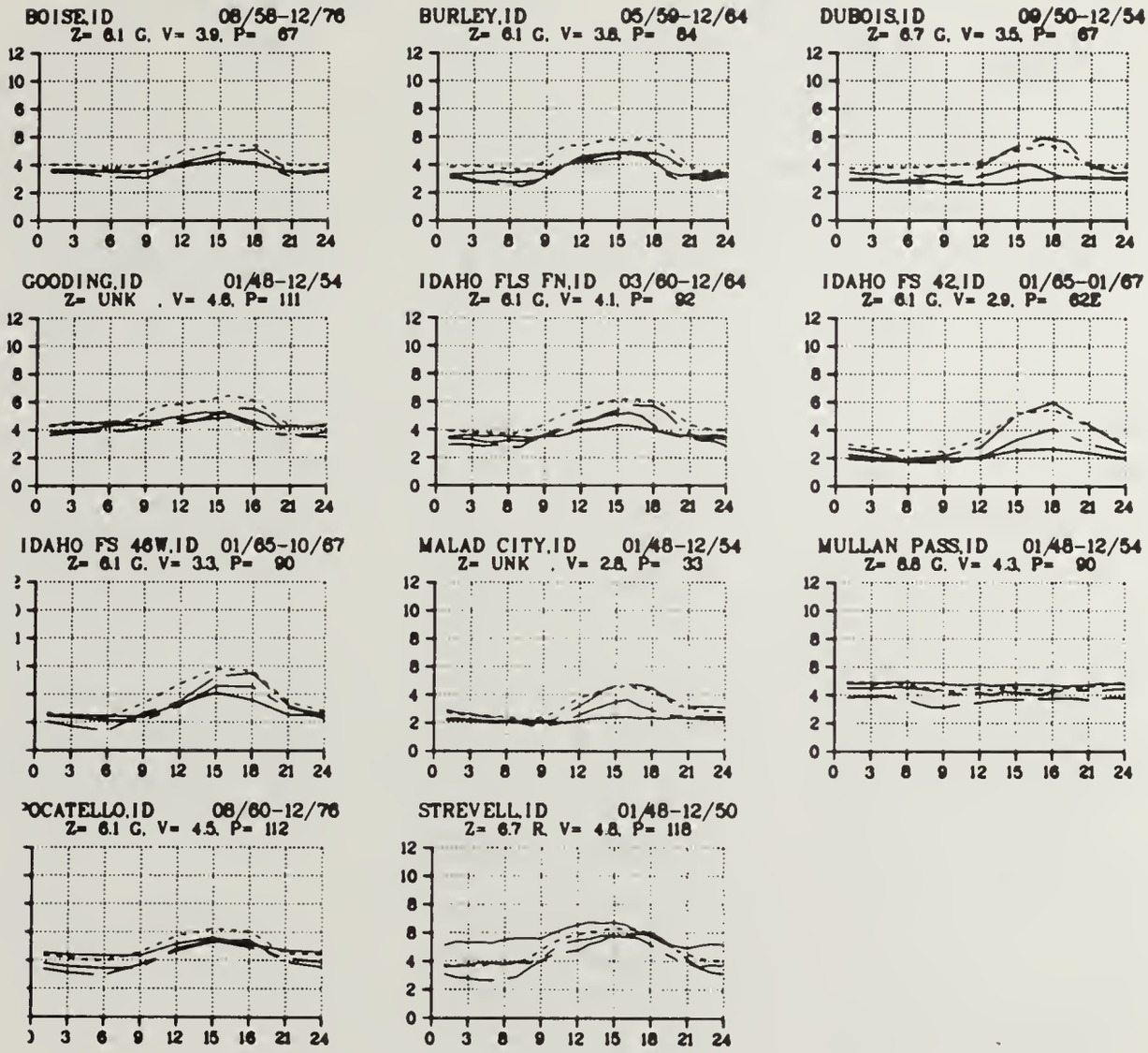


FIGURE 4.12. Diurnal Wind Speed by Season for Idaho

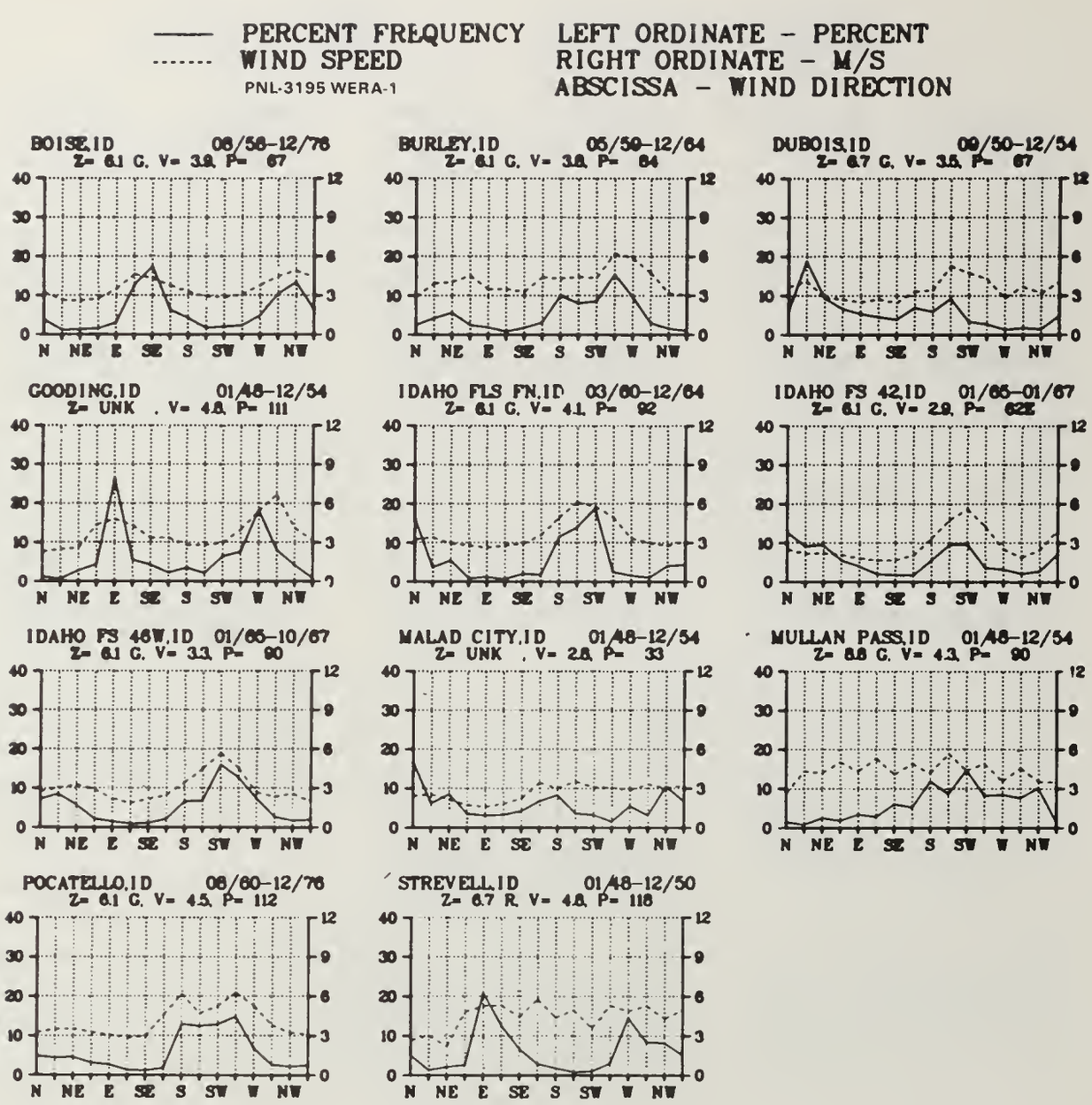


FIGURE 4.13. Directional Frequency and Average Wind Speed for Idaho

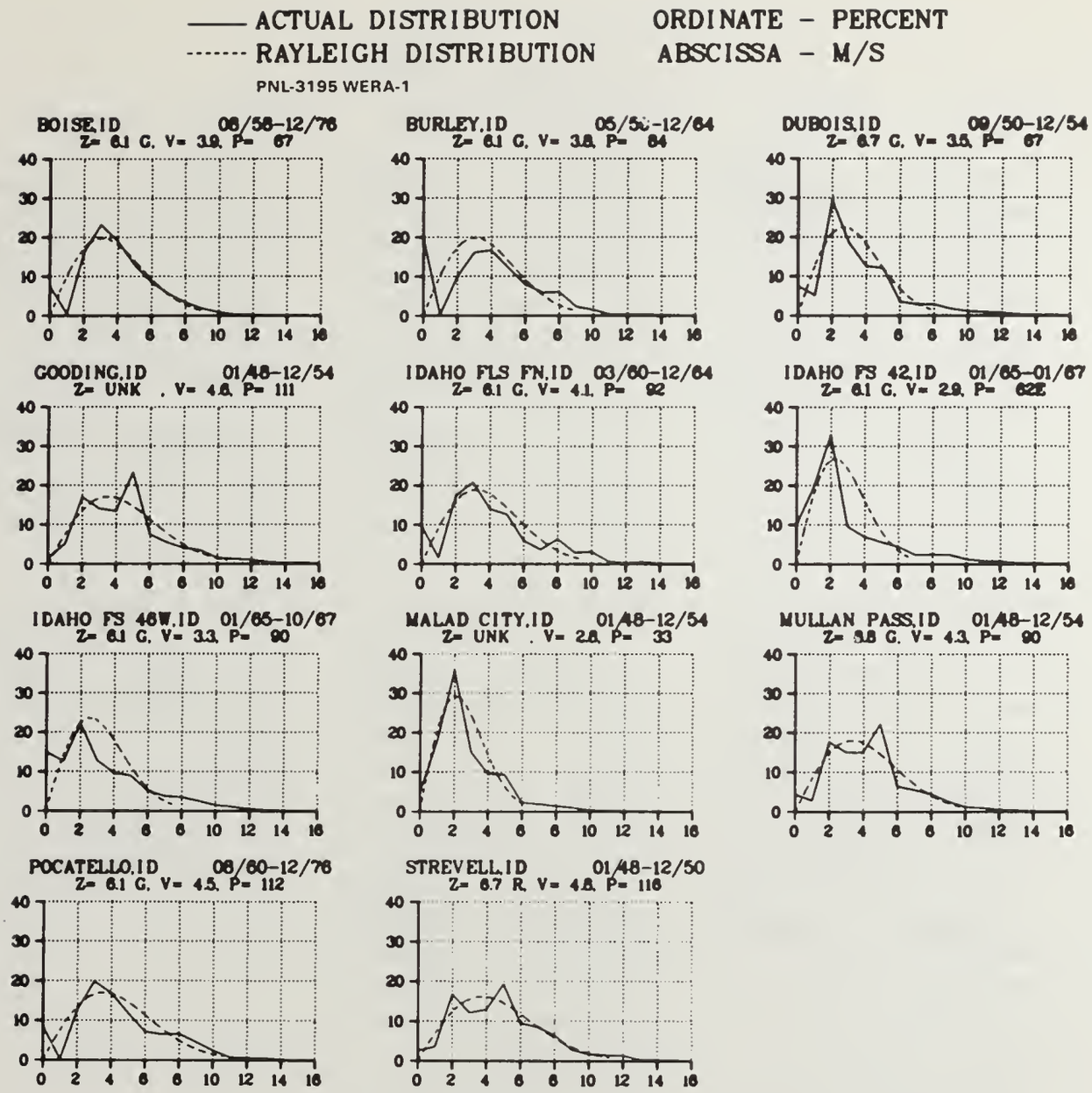


FIGURE 4.14. Annual Average Wind Speed Frequency for Idaho

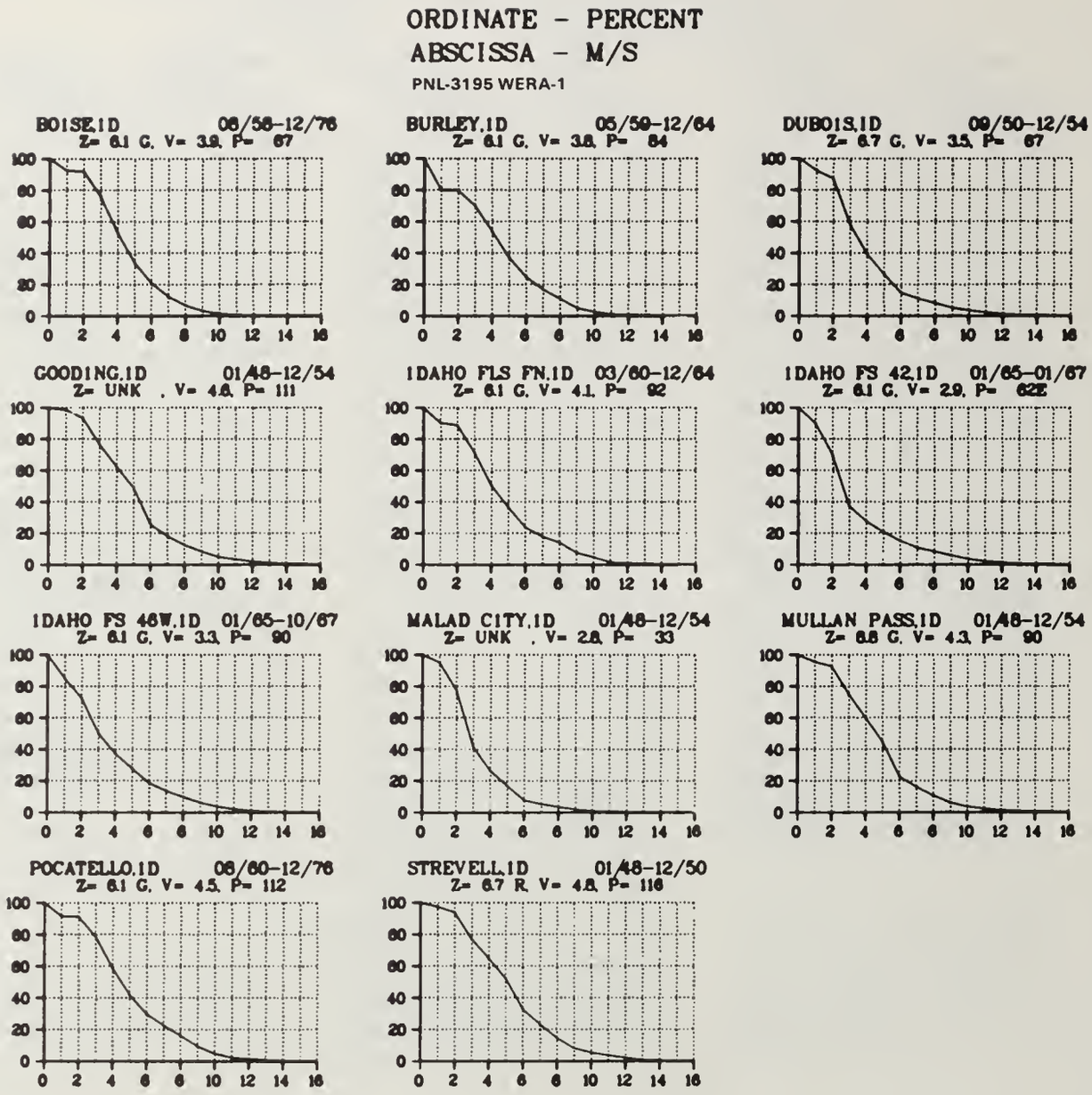


FIGURE 4.15. Annual Average Wind Speed Duration for Idaho

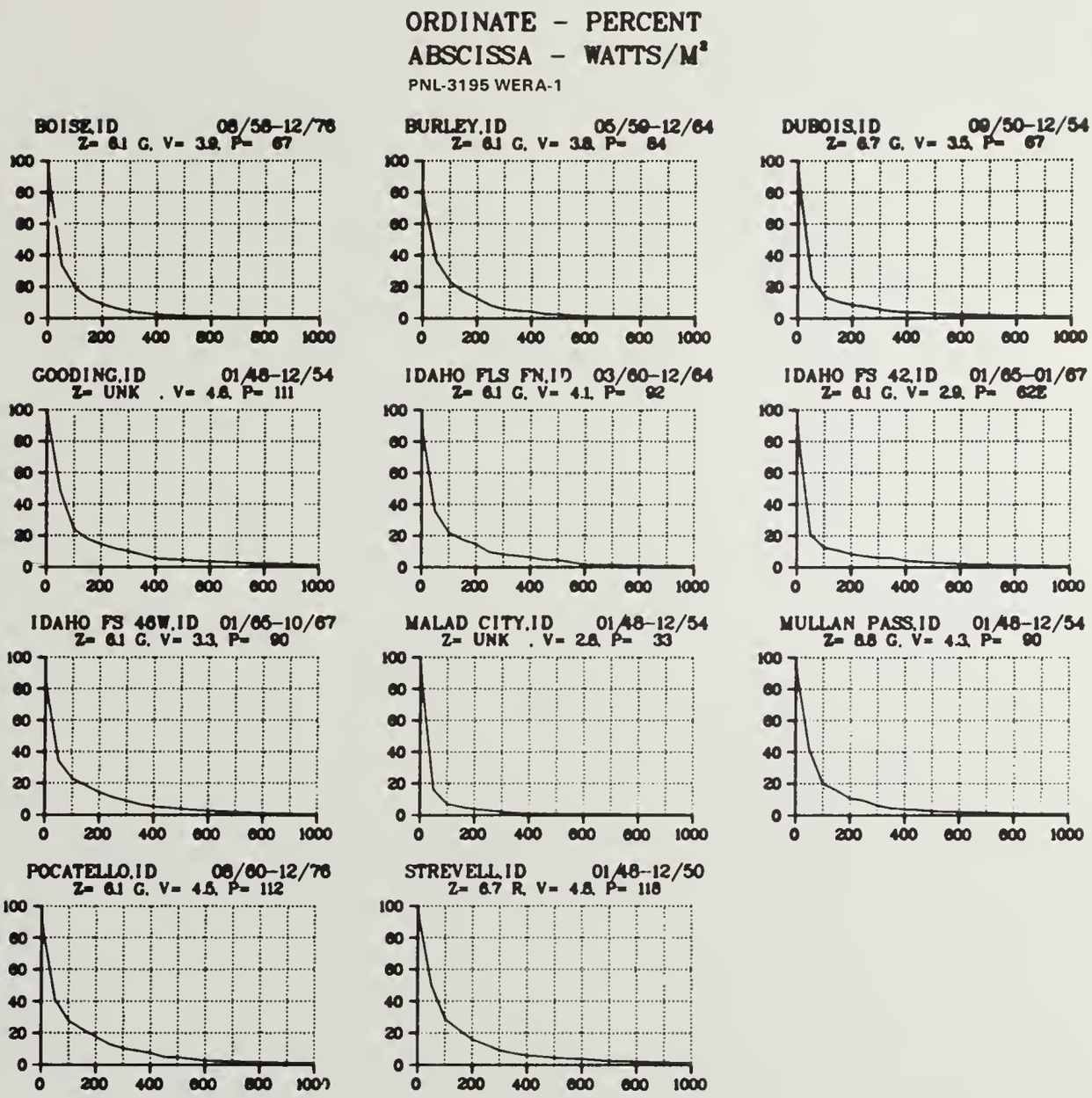


FIGURE 4.16. Annual Average Wind Power Duration for Idaho

MONTANA

CHAPTER 5: MONTANA

Montana, which had a population of 694,409 in 1970, covers 381,087 km^2 (147,138 mi^2). Its largest cities--Billings and Great Falls--have populations over 60,000 and are located east of the Rocky Mountains along broad river valleys (see Figure 5.1). However, some major cities, e.g., Helena and Missoula, are located in the Rocky Mountains.

Much of western Montana is characterized by mountainous terrain, whereas in eastern Montana open hills, plains and broad river valleys are the predominant terrain features (Figure 5.2). Local relief exceeds 1,000 m (3,000 ft) throughout the Rocky Mountains. Relief east of the mountains varies from 90 to 300 m (300 to 1,000 ft), as shown in Figure 5.3.

Available wind data from the National Climatic Center (NCC) are mostly from stations along the major highway routes and near population centers (Figure 5.4). Large areas exist throughout the state where no year-round data or only limited unsummarized data are available (Figure 5.5). Fire weather data are abundant in the mountainous regions, but only those stations for which more than 70% of the single daily observations during the fire season exceeded 3.5 m/s are used.

5.1 ANNUAL AVERAGE WIND POWER

The valley areas in the vicinity of Livingston and Whitehall have class 6 annual average wind energy (Figure 5.6). The highest wind power usually occurs at the mouths of these long southwest- to northeast-oriented valleys. For example, data from Dillon indicate a decrease in wind power up-valley from the mouth of the valley near Whitehall. This phenomenon may occur in other valleys with similar topography. Sheltered basins and valleys that have constricted mouths or that do not drain toward the north, northeast or east have class 1 or 2 wind energy. For example, Missoula, Kalispell, Helena, Butte, and Bozeman are all located in sheltered valleys or basins. For valley areas without wind data, the length, orientation and other topographic characteristics of the valleys were used as indicators to infer the wind power potential (Elliott 1979a). However, the wind power may vary dramatically over short distances in areas of complex terrain.

The plains east of Glacier National Park are estimated to have class 5 annual average wind power, based on wind data for Cut Bank, Montana and Lethbridge, Alberta. Class 4 wind power extends from east of Cut Bank south to Great Falls. Although the meteorological conditions that produce the strong west-to-southwest winds at Great Falls and Cut Bank also appear to exist in the plains just to the east of the Rocky Mountains in Montana, the geographic variability of the wind energy resource is uncertain. The plains near the base of the Rockies may be sheltered from the prevailing strong west-to-southwest winds found at Great Falls and Cut Bank, 70 km (45 mi) from the mountains. Class 4 wind power is also expected near Harlowton and Big Timber (see Figure 5.4 for locations) as strong westerly winds frequently extend eastward from mountain corridors.

Two ridge areas in eastern Montana (shaded on Figure 5.6) are estimated to have class 4 wind power although no wind data were identified in these areas. Other hilltops and ridge crests could also have class 4 power in eastern Montana. Exposed locations on the plains and uplands of eastern Montana are estimated to have at least class 3 power.

Lowland areas, such as the Powder River valley in southeastern Montana, have class 2 or lower wind power, based on the available wind data in these areas. However, in broad valleys aligned parallel to the prevailing strong west-to-northwest winds, exposed locations may have the same power class as upland areas (e.g., Glasgow Airport compared to Glasgow Air Force Base; see Table 5.2).

Airport runway directions and wind direction data indicate the prevailing surface winds are northwest and southeast in eastern Montana (east of a line from Havre to Custer), even in major river valleys oriented southwest and northeast, e.g. the Yellowstone River Valley east of Miles City. However, existing data indicate that even in regions of gently sloping terrain, broad valleys that are oriented parallel to the prevailing strong winds have higher wind power than valleys that are not. From the line joining 109°W longitude at the Canadian border with 107°W longitude at the Wyoming border westward to the Rocky Mountains, the prevailing strong winds are generally west to southwest, with weaker easterly flow. However, prevailing surface wind direction(s) near the mountains may be strongly influenced by the mountains (e.g., at Lewiston). Areas near the base of extensive mountain ranges such as in the class 2 area east of the Bighorn Mountains may even be shielded from the strong westerly winds that occur over the plains east of the Rockies (except where wind corridors may extend down from the mountains).

Exposed mountain summits and ridge crests in the Rocky Mountains are estimated to have at least class 4 to class 6 annual average wind power. Summits near 1,800 m (6,000 ft) may have class 4 wind power while summits near 3,000 m (9,000 ft) may have class 6 or greater power.

5.1.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power estimates for Montana vary from 1 to 4 (Figure 5.7). Only two areas have class 4 or greater wind power and a certainty rating of 4: the Cut Bank and Great Falls areas. However, the certainty rating decreases from 4 to 2 within a few grid cells of these areas because of the lack of data and the uncertain influence of the Rocky Mountains on the geographical variability of this high wind resource. The wind power estimates over the plains near the base of the Rocky Mountains have a certainty rating of only 1, because of the extreme variability of the wind resource that may occur in these areas and the lack of data.

The high wind corridors near Livingston and Whitehall in southwest Montana have a certainty rating of only 2 because of the high complexity of the terrain and large variability of the resource in these areas. Some of the valleys and basins in southwestern Montana have been given a certainty rating of 1 because of a lack of data in these areas.

The plains in the vicinities of Havre, Glasgow, Wolf Point, and Billings are assigned certainty ratings of 4 because the existing data appears representative of nearby exposed areas. Although most of the nonmountainous terrain of eastern Montana is plains, tablelands, or gently rolling hills, much of this area is without any representative wind data and thus has a certainty rating of only 2.

Although no year-round data were available from exposed sites in mountainous terrain, the mountain summit and ridge crest estimates are given a certainty rating of 2 because upper-air wind data were used to approximate the power in these areas.

5.1.2 Areal Distribution

The wide variety of land-surface forms and wind power regimes makes the areal distribution of wind power in Montana difficult to represent. For example, not all of the mountain valleys could be resolved with the grid size used in this analysis. The impact of the large plains area with class 3 or higher wind power is immediately apparent in Table 5.1, which shows that about 41% of the state has class 3 or higher power. Figure 5.8 further reinforces the summary of Table 5.1 by indicating that grid cells in the plains of the eastern two-thirds of Montana have class 3 or higher wind power over about 33% of their area, on the average. The mountains of western Montana contribute only about 1.2% of the 3.9% of the land area with class 5 or better wind power; the remainder (2.7%) is found over the northwestern plains.

The low percentage of area with class 2 wind power in Table 5.1 occurs because few areas of the state were assigned class 2 wind power. Furthermore, the wind power scale factor employed in the high relief land-surface forms of the mountainous areas reduced the mountain summit and ridge crest class 5 and 6 estimates to class 1 in the most sheltered exposure category. The maps of Figure 5.8 and data in Table 5.1 illustrate this situation.

5.2 SEASONAL WIND POWER

Wind power maps for each season are shown on facing pages in Figure 5.9. Winter is the season of maximum wind power over the exposed ridge crests and mountain summits in the Rocky Mountains, the wind valley corridors in southwestern Montana, and the central Montana plains from Billings north to Havre and west to the base of the Rockies. East of Billings in the south to east of Havre in the north, spring is the season of maximum wind power. Summer is the season of least wind power throughout all of Montana.

5.2.1 Winter

During the winter, class 7 wind power occurs in the Whitehall and Livingston corridor areas in southwestern Montana. Exposed ridge crests in the Rocky Mountains are also estimated to have class 7 wind power in winter, based on upper-air data and data from a few mountain summit stations. However, weather conditions make it difficult to reach the ridge crests or summits in these high mountain areas during the winter.

In winter, class 6 power is found in the plains east of the Rockies extending northward from Great Falls to the Canadian border. The corridor west of Harlowton is also estimated to have class 6 power, although no wind data were available in this area. The winter average wind power decreases to class 4 over central Montana and to class 3 over eastern Montana.

Over the plains within 150 to 200 km (90 to 125 mi) of the Rockies, the prevailing strong winds are generally west to southwest

in winter. These winds are often associated with strong surface pressure gradients across the eastern slopes of the Rockies, which sometimes extend from central Alberta to Wyoming. Pressure gradient forces appear to accelerate the flow down the long valley corridors of southwestern Montana and down the lee slopes of the Rockies and across the plains of northwestern Montana. Strong surface winds in these areas also frequently occur when strong westerly winds aloft are present.

Most sheltered valleys and basins in the Montana Rockies have generally low wind speeds similar to those at Bozeman and Butte. However, valley stations located near gaps, passes, or mountain drainage outlets may experience occasional strong winds. For example, Kalispell Glacier Park International Airport occasionally experiences very strong northeasterly winds during the winter. These winds are channeled down the Flathead River valley from the Glacier National Park area. The synoptic weather patterns associated with these strong northeast winds occur less frequently than the weather patterns associated with strong southwest winds in the Whitehall and Livingston areas.

5.2.2 Spring

Class 5 wind power is apparent in the windy corridors in southwestern Montana and the plains near Cut Bank. The strongest winds during spring are usually from the northwest over most of eastern Montana. Class 4 power occurs over most of the northern Montana plains and eastern Montana. Rocky Mountain ridge crests have at least class 4 to 6 wind power in the spring. However, the upper-air wind speeds are lower in spring than in the winter.

5.2.3 Summer

The highest summer wind power, class 3, occurs in the plains around Cut Bank, the Whitehall corridor, and the higher exposed ridge crests and mountain summits in the Rockies. However, some of the data from fire weather stations in the Montana Rockies indicate wind powers of 200 to 500 watts/m^2 at anemometer height, based on one afternoon observation per day during the fire weather season. At some of these stations, the free air flow is probably accelerated by the topography.

5.2.4 Autumn

The autumn map shows the highest wind energy to be in the windy corridors of the Whitehall and Livingston areas, over the plains of the Great Falls-Cut Bank area, and on the exposed ridge crests in the Rocky Mountains.

5.3 FEATURES OF SELECTED STATIONS

Table 5.2 gives the location and annual wind speed and power density of seventeen stations in Montana. Graphs of other features of the wind resource are shown in Figures 5.10 to 5.16. Multiple stations were selected in the Great Falls, Havre, and Glasgow areas to examine local variations in a plains environment.

Billings Airport, in the broad Yellowstone River valley of southcentral Montana, is located on a shelf 100 to 150 m (300 to 450 ft) higher than most of the city. The site is well exposed to the prevailing west-southwest winds, which appear to flow down the Yellowstone River valley from the Rocky Mountains.

Bozeman Airport, in southwestern Montana, is located in a sheltered basin where mean wind speeds are generally light. The airport data are expected to be representative only of the immediate basin area.

Butte, as with Bozeman, is located in a sheltered valley in southwestern Montana. However, in nearby areas the terrain may channel and enhance the wind speeds (e.g., wind corridors). About 15 to 25 km (10 to 15 mi) east-southeast of Butte in the Beaverhead Valley (near Whitehall), the wind energy is considerably greater than at Butte.

Cut Bank is situated in the Great Plains about 60 km (40 mi) east of the base of the Rocky Mountains in northwestern Montana. The station frequently experiences strong west to west-southwest winds, especially during the colder months. The wind characteristics at Cut Bank may be fairly representative of the area from about 75 km (45 mi) south of Cut Bank north to the Canadian border. However, areas near the base of the Rocky Mountains (except for long valley outlets) may be sheltered from these strong westerly winds.

Dillon is located near the head of the Beaverhead River valley in the Rocky Mountains of southwestern Montana. Data from Dillon and Whitehall indicate the wind power increases considerably down the valley towards Whitehall.

The Glasgow area in northeastern Montana is represented by three stations: Glasgow International Airport, Glasgow Air Force Base, and Glasgow Weather Bureau Office (1948-1955). Both the Glasgow International Airport and Glasgow Air Force Base appear representative of exposed sites. However, the Glasgow Weather Bureau Office, located in the city of Glasgow, has considerably lower mean wind speed and power than do the airport and Air Force base (see Table 5.2).

The Great Falls International Airport has considerably greater wind power at 10 m (30 ft) than does the Malmstrom Air Force Base. However, the airport sits on a plateau about 70 m (250 ft) higher than most of the immediate valley area, which includes the city of Great Falls and the Malmstrom Air Force Base. The airport is well exposed to the prevailing southwest winds and is estimated to have higher wind power than the city of Great Falls.

Havre is located in the Milk River plains area in northcentral Montana. The airport site is well exposed to the prevailing wind directions and indicates more than double the wind power of the city site.

Lewiston, located in central Montana east of the Rocky Mountains, is in a basin that is partially sheltered by the surrounding hills and mountains.

Livingston is situated at the mouth of a long valley wind corridor in the Rocky Mountains of southwestern Montana. Wind energy is at least class 6 during the colder months, when strong winds are channeled and enhanced down the Yellowstone Valley. However, the wind power may vary dramatically throughout the area near the Livingston Airport because of the complex topography.

Miles City is situated in a shallow part of the Yellowstone River valley in the rolling hills of southeastern Montana. Upland areas are estimated to have about one class higher wind power than that of the airport, which is in the valley.

Superior, located in a narrow, deep canyon in the mountains of northwestern Montana, appears shielded from the air flow in all directions. This station's wind characteristics are probably typical of most sites in narrow, deep valleys in mountainous terrain.

Whitehall is situated in southwestern Montana at the mouth of a long valley that extends south-southwest for about 125 km (80 mi). Strong down-valley winds frequently occur in this area, especially during the colder months.

5.3.1 Interannual Wind Power and Speed

Large interannual variations in wind power occur at some of the stations, particularly Livingston, Whitehall, and Great Falls International Airport (Figure 5.10). At Whitehall, for example, the interannual variations span four classes of wind power (classes 4 to 7). At Great Falls, the annual wind power did not exceed 160 watts/m^2 for five consecutive years (1965 to 1969), whereas the annual wind power did not go below 220 watts/m^2 during any of the 6 years from 1971 through 1976. Thus, 1 or even 2 years' data may not give a reliable estimate of the long-term average wind power in areas with large interannual variations.

At some stations, the interannual variations are relatively small, with less than 50% difference in power between the years of lowest and highest wind power, e.g., Glasgow International, Billings, Lewiston, and Havre. However, the interannual variations presented here may not be representative or typical of other periods of record at the same stations. For example, at Great Falls Airport, the interannual variability of wind power was substantially less during the period 1942 to 1958 than it was during the period 1960 to 1976.

5.3.2 Monthly Average Wind Power and Speed

Livingston and Whitehall experience class 7 wind power in winter. Both of these stations are located at the outlets of long river valleys and show pronounced seasonal variations (see Figure 5.11). Dillon, located 85 km (50 mi) up-valley from Whitehall, has a smaller seasonal variation than does Whitehall. Although the 4-year period of record presented for Dillon indicates little difference between the winter and spring power, the 16-year period from 1948 to 1963 shows a distinct winter maximum at Dillon.

Butte, located in a sheltered basin only about 35 km (22 mi) west-northwest of Whitehall, experiences maximum wind power in the spring. Likewise Bozeman, located in a sheltered basin between Livingston and Whitehall, has seasonal trends much different from Livingston and Whitehall.

Cut Bank, Great Falls, Lewiston, and Billings all show winter maxima. This seasonal trend appears characteristic of the Montana plains extending 100 to 200 km (60 to 120 mi) east from the Rocky Mountains. Glasgow and Miles City are characteristic of the seasonal trends in eastern Montana, where spring is the season of highest wind power. Havre, located in the transition zone, has power that is about equal in the winter and spring.

5.3.3 Diurnal Wind Speed by Season

All 17 stations presented for Montana indicate maximum wind speeds during the afternoon or early evening for all seasons (Figure 5.12). In winter, the diurnal variations are smaller and peak speeds occur about 1500 local standard time (LST), except at Livingston, which shows a peak at

1200 LST. Maximum diurnal variations occur during the spring and summer season at most stations, with peak speeds around 1500 to 1800 LST. Average afternoon wind speeds exceed 6 m/s during the summer at Livingston and Whitehall. During the autumn, the largest diurnal trends resemble those of winter more than those of spring and summer for most stations, with peak speeds around 1500 LST.

5.3.4 Directional Frequency and Average Speed

Strong west-to-southwest winds prevail at most of the stations in western Montana (Figure 5.13). At Livingston and Whitehall, annual average wind speeds from the south-southwest exceed 10 m/s. Moreover, the strongest winds are from the same direction as the prevailing winds as indicated by the coincidence of peaks in the directional frequency and mean speed curves. A unique combination of topography and frequently occurring weather conditions causes the strong down-valley south-southwesterly winds in the Livingston and Whitehall area.

The weather conditions that result in the strong south-southwesterly winds in the Whitehall and Livingston corridors also produce strong west-to-southwest winds over the plains immediately east of the Rocky Mountains (e.g., at Cut Bank, Great Falls, Havre, Lewiston, and Billings). In eastern Montana, the prevailing strong winds are mostly northwest and southeast. Long ridges and slopes that are oriented perpendicular to these directions may enhance the wind power.

5.3.5 Annual Average Wind Speed Frequency

Observer biases are evident in the actual distributions for Bozeman, Glasgow Weather Bureau Office, Livingston, and Whitehall (Figure 5.14). Some of the other stations also show indications of observer bias in the recorded observations. This bias is often reflected in the peaks at 2, 5, and 8 m/s (5, 10 and 15 knots) at stations with periods of record in the 1940s and 1950s.

Dramatic differences exist in the observed frequency distribution between Havre Weather Bureau Office (city) and Havre City-County Airport and between Glasgow Weather Bureau Office (city) and Glasgow International Airport. The city locations have substantially lower wind speed and power than do the airport locations, even though the height of the wind instruments is lower at the airport.

5.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 5.15 and 5.16. Abrupt changes in the slope of the duration curves usually correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

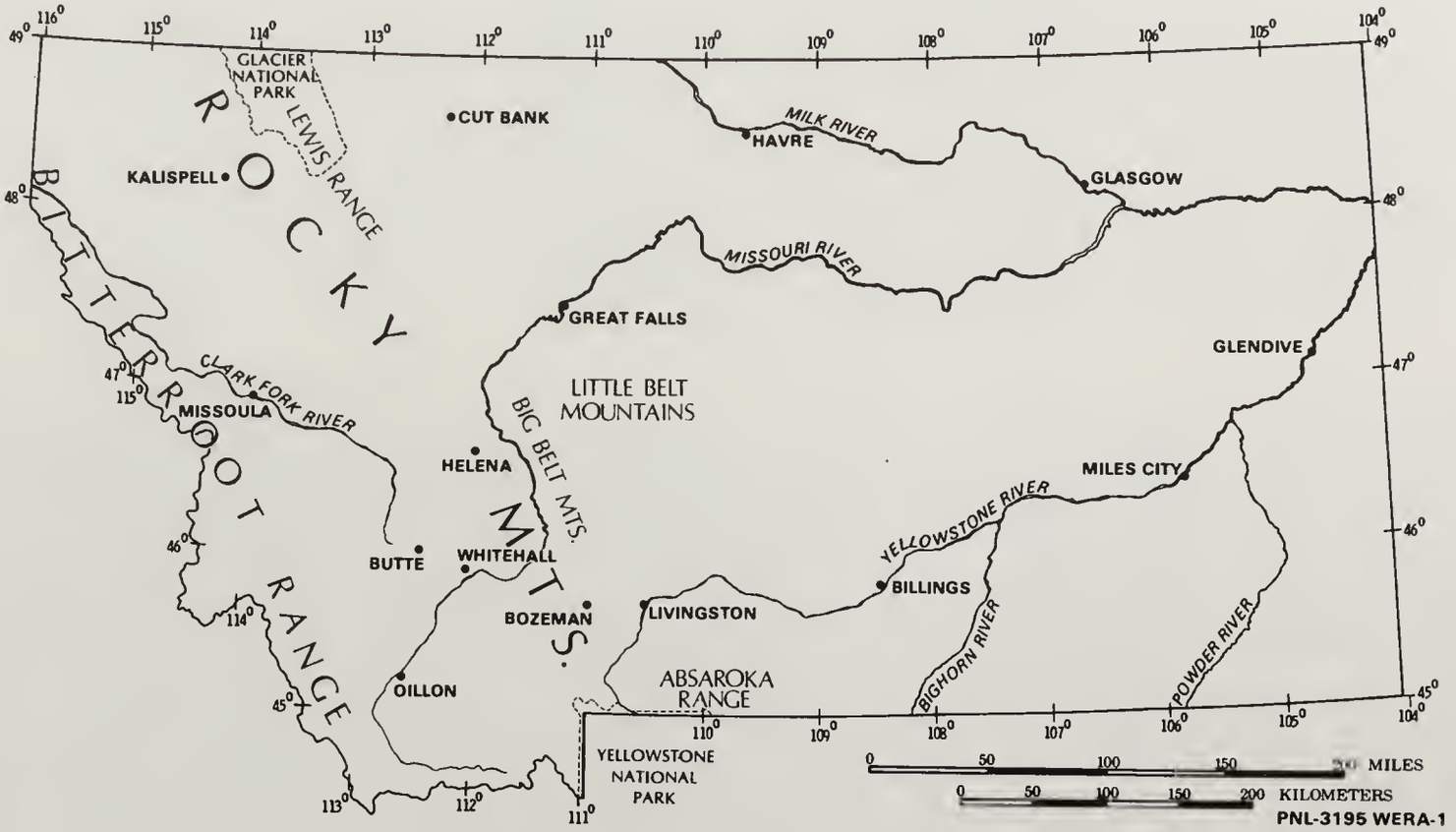


FIGURE 5.1. Geographic Map of Montana

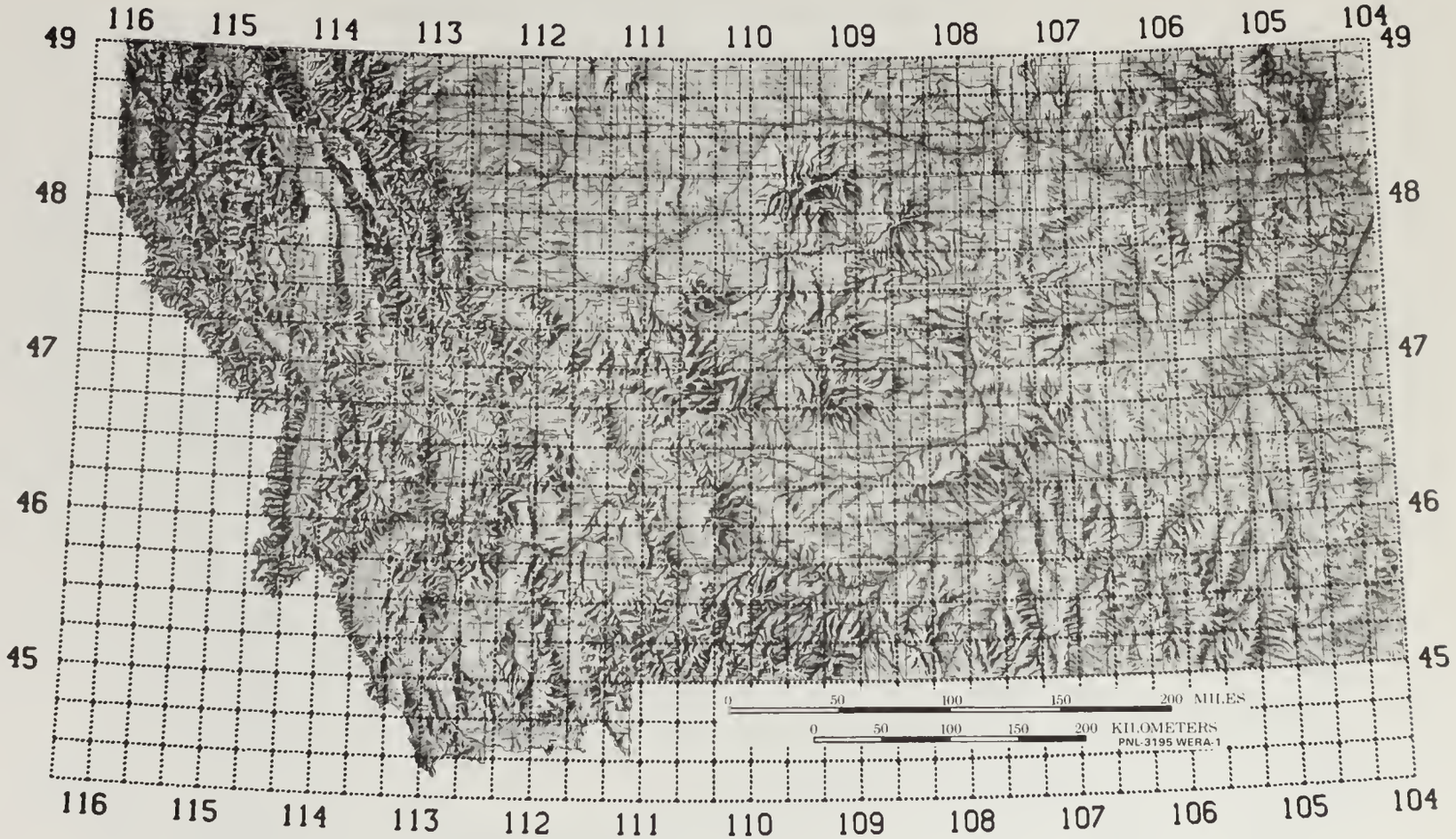


FIGURE 5.2. Topographic Map of Montana

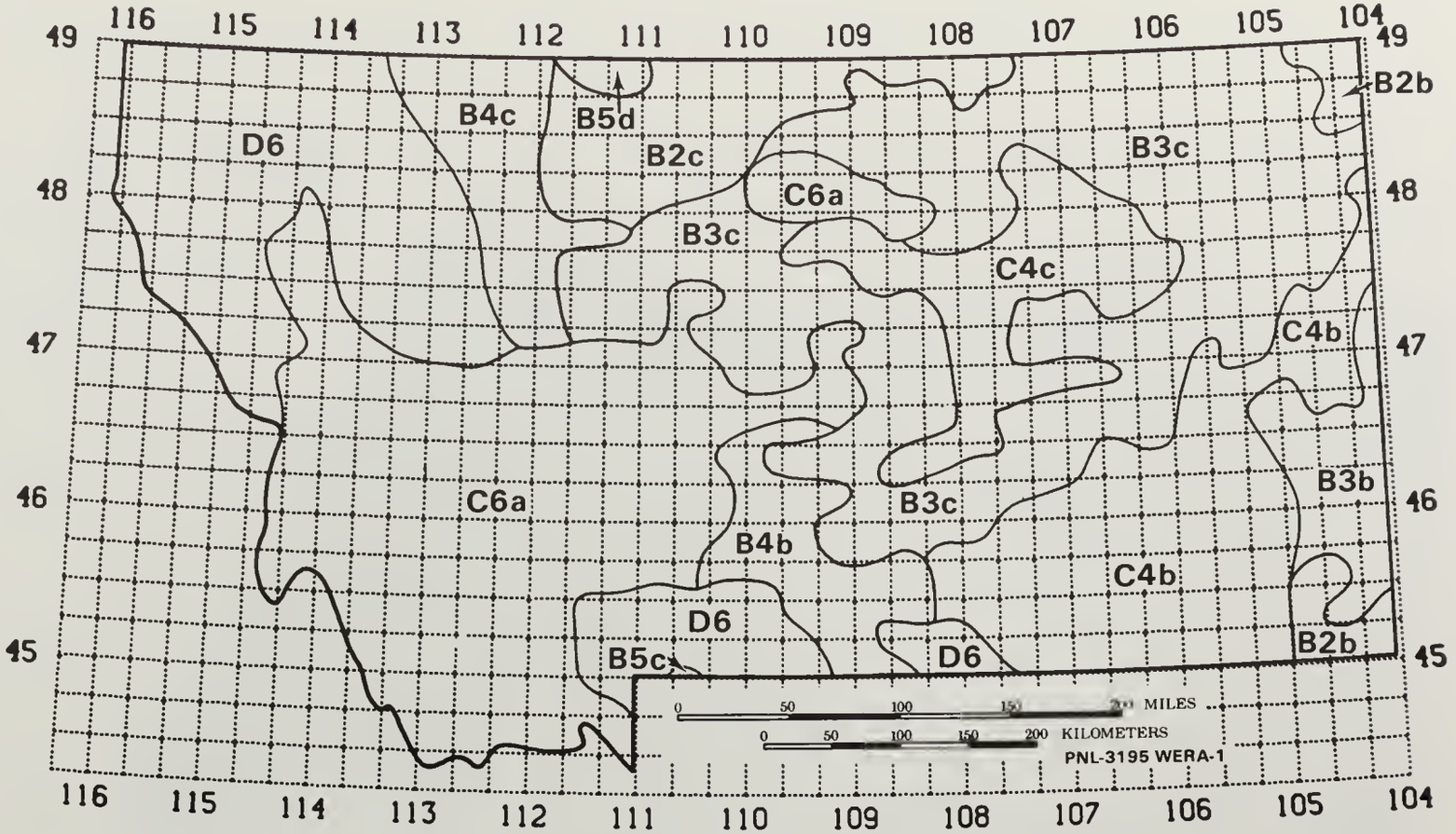


FIGURE 5.3. Land-Surface Form Map for Montana

LAND-SURFACE FORM LEGEND

PLAINS

A1	FLAT PLAINS
A2	SMOOTH PLAINS
B1	IRREGULAR PLAINS, SLIGHT RELIEF
B2	IRREGULAR PLAINS

PLAINS WITH HILLS OR MOUNTAINS

A,B3a,b	PLAINS WITH HILLS
B4,a,b	PLAINS WITH HIGH HILLS
B5a,b	PLAINS WITH LOW MOUNTAINS
B6a,b	PLAINS WITH HIGH MOUNTAINS

OPEN HILLS AND MOUNTAINS

C2	OPEN LOW HILLS
C3	OPEN HILLS
C4	OPEN HIGH HILLS
C5	OPEN LOW MOUNTAINS
C6	OPEN HIGH MOUNTAINS

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

TABLELANDS

B3c,d	TABLELANDS, MODERATE RELIEF
B4c,d	TABLELANDS, CONSIDERABLE RELIEF
B5c,d	TABLELANDS, HIGH RELIEF
B6c,d	TABLELANDS, VERY HIGH RELIEF

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

A	>80% OF AREA GENTLY SLOPING
B	50-80% OF AREA GENTLY SLOPING
C	20-50% OF AREA GENTLY SLOPING
D	<20% OF AREA GENTLY SLOPING

LOCAL RELIEF (2nd LETTER)

1	0 TO 30m (1 TO 100 ft)
2	30 TO 90m (100 TO 300 ft)
3	90 TO 150m (300 TO 500 ft)
4	150 TO 300m (500 TO 1000 ft)
5	300 TO 900m (1000 TO 3000 ft)
6	900 TO 1500m (3000 TO 5000 ft)

PROFILE TYPE (3rd LETTER)

a	>75% OF GENTLE SLOPE IS IN LOWLAND
b	50-75% OF GENTLE SLOPE IS IN LOWLAND
c	50-75% OF GENTLE SLOPE IS ON UPLAND
d	>75% OF GENTLE SLOPE IS ON UPLAND

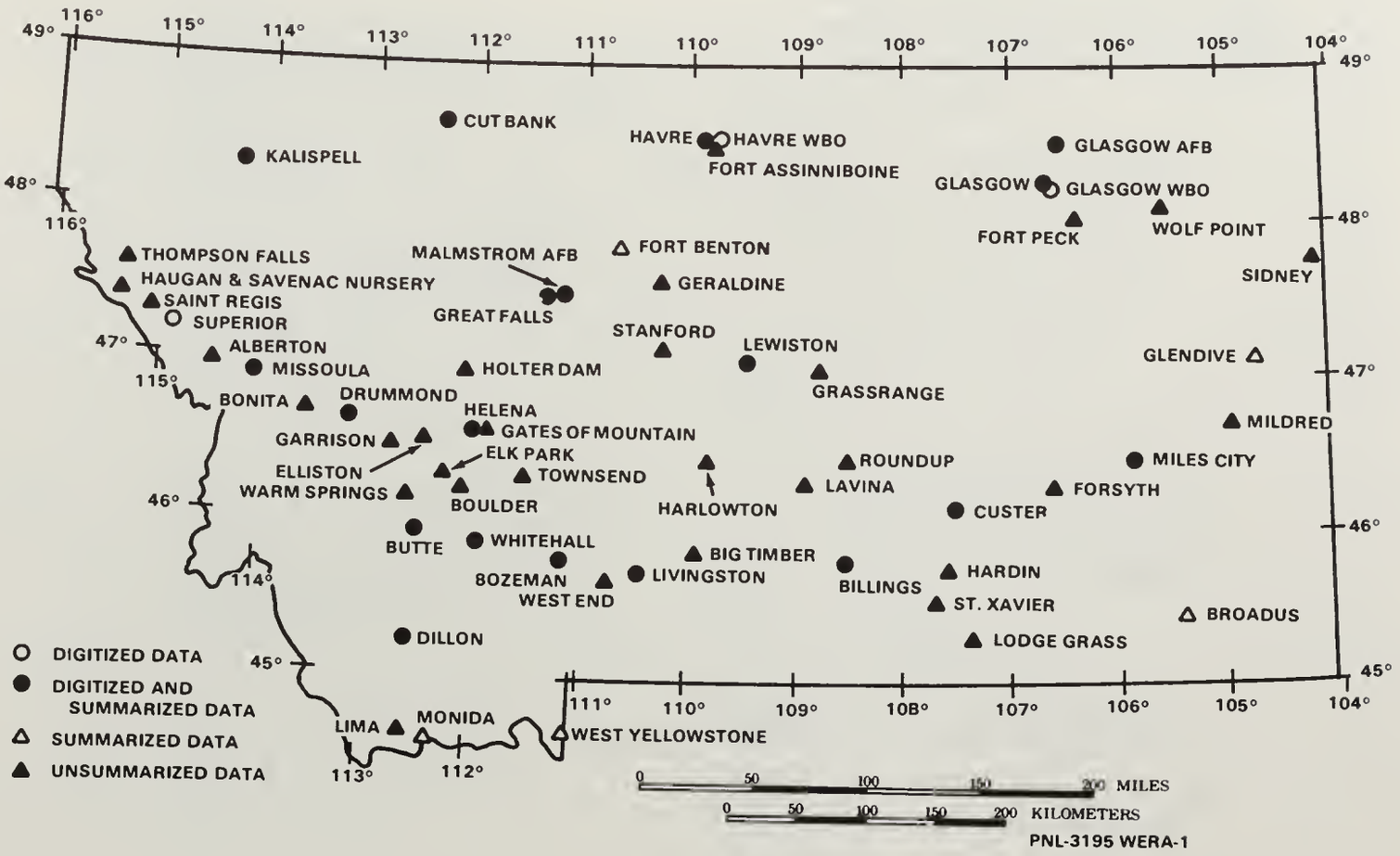


FIGURE 5.4. NCC Station Locations in Montana

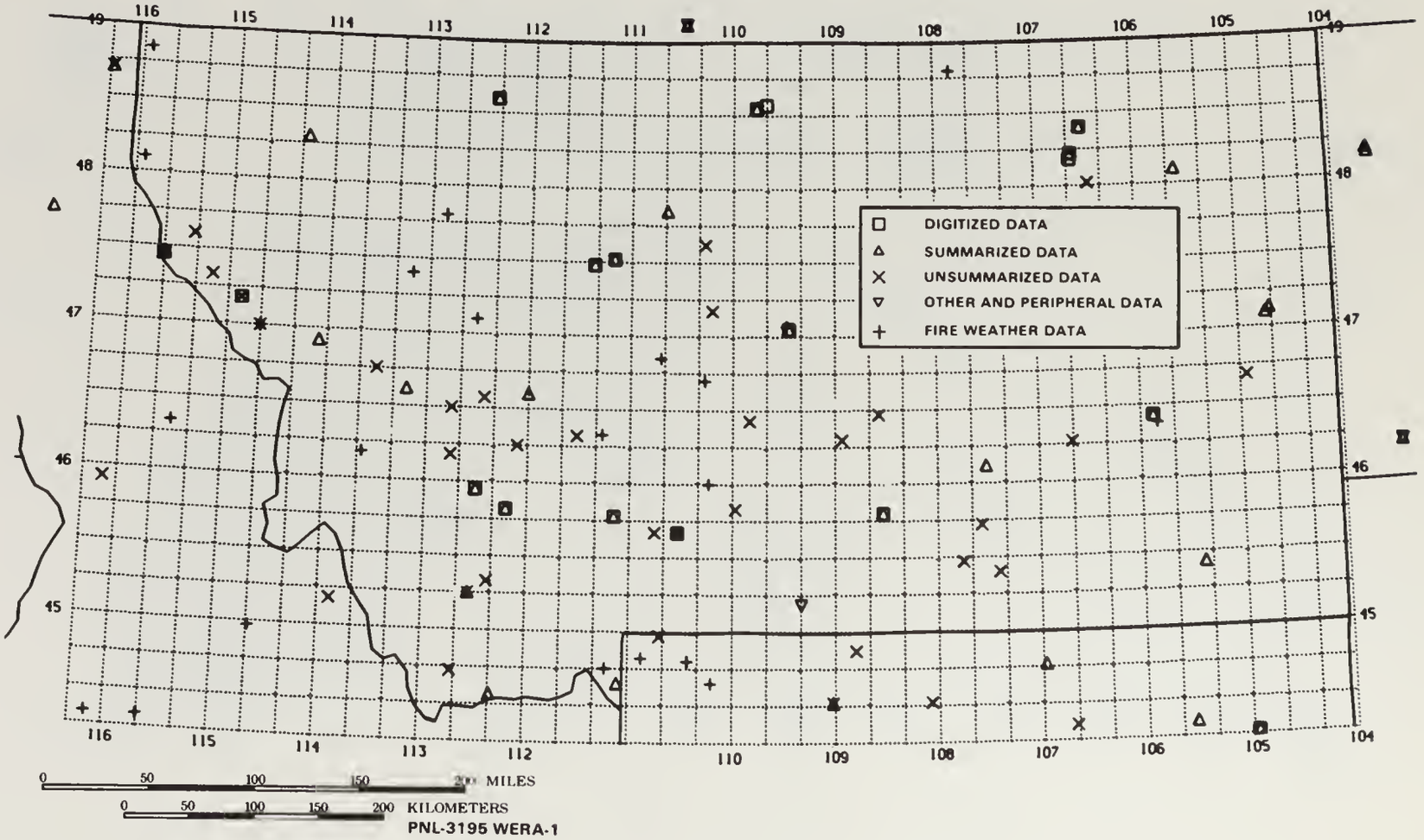


FIGURE 5.5. Location of Stations Used in Montana Resource Assessment

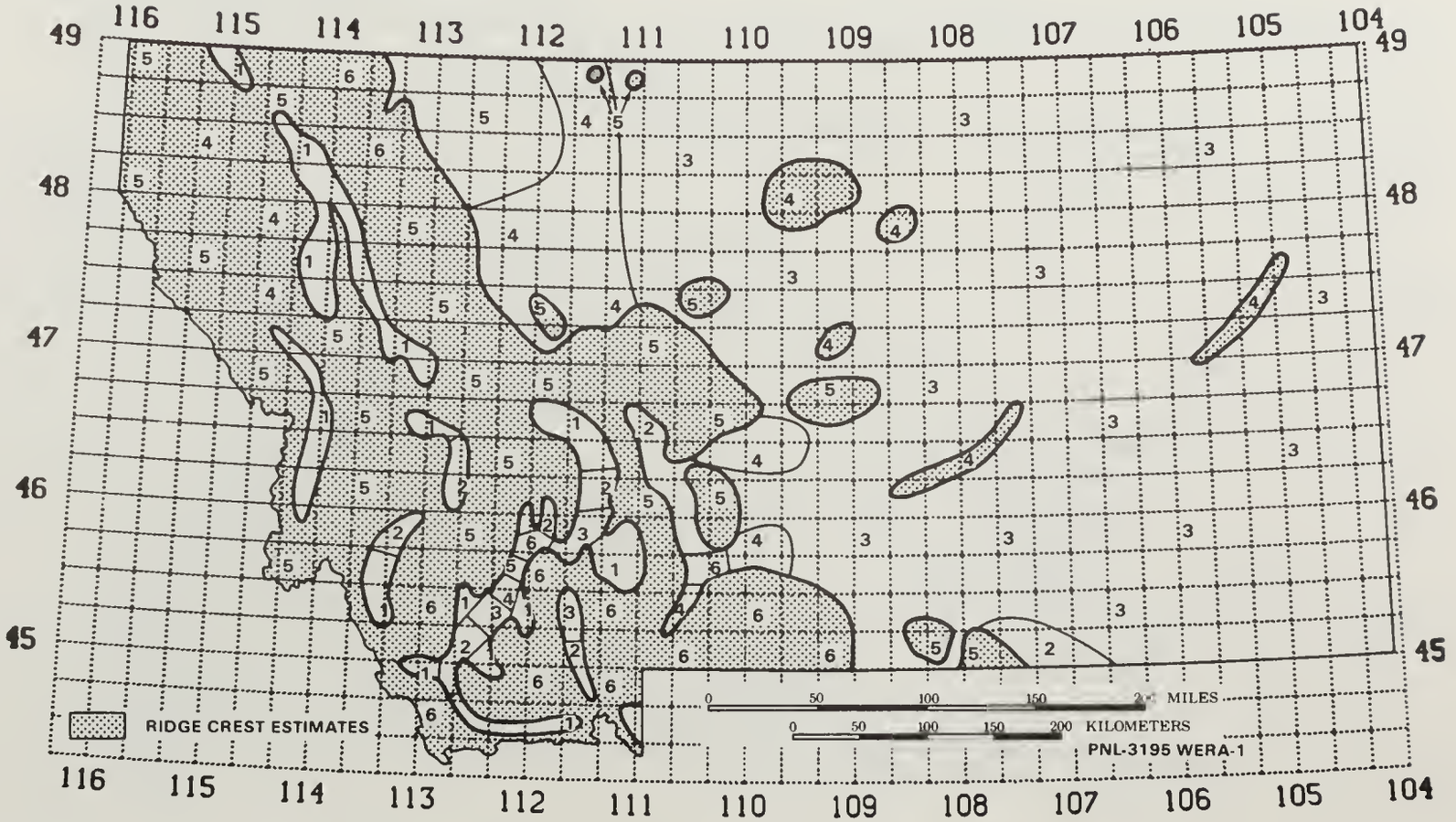


FIGURE 5.6. Montana Annual Average Wind Power

Classes of Wind Power Density at 10 m and 50 m[a]

Wind Power Class	10 m (33 ft) Wind Power Density, watts/m²	10 m (33 ft) Speed,[b] m/s (mph)	50 m (164 ft) Wind Power Density, watts/m²	50 m (164 ft) Speed,[b] m/s (mph)
1	0	0	0	0
2	100	4.4 (9.8)	200	5.6 (12.5)
3	150	5.1 (11.5)	300	6.4 (14.3)
4	200	5.6 (12.5)	400	7.0 (15.7)
5	250	6.0 (13.4)	500	7.5 (16.8)
6	300	6.4 (14.3)	600	8.0 (17.9)
7	400	7.0 (15.7)	800	8.8 (19.7)
	1000	9.4 (21.1)	2000	11.9 (26.6)

(a) Vertical extrapolation of wind speed based on the 1/7 power law.
(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 5.1. Areal Distribution (km^2) of Wind Power Classes in Montana

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	220,000	57.	380,000	100.
2	7,900	2.1	160,000	43.
3	130,000	33.	150,000	41.
4	14,000	3.8	29,000	7.7
5	12,000	3.2	15,000	3.9
6	2,500	0.65	2,500	0.65
7	0	0.00	0	0.00

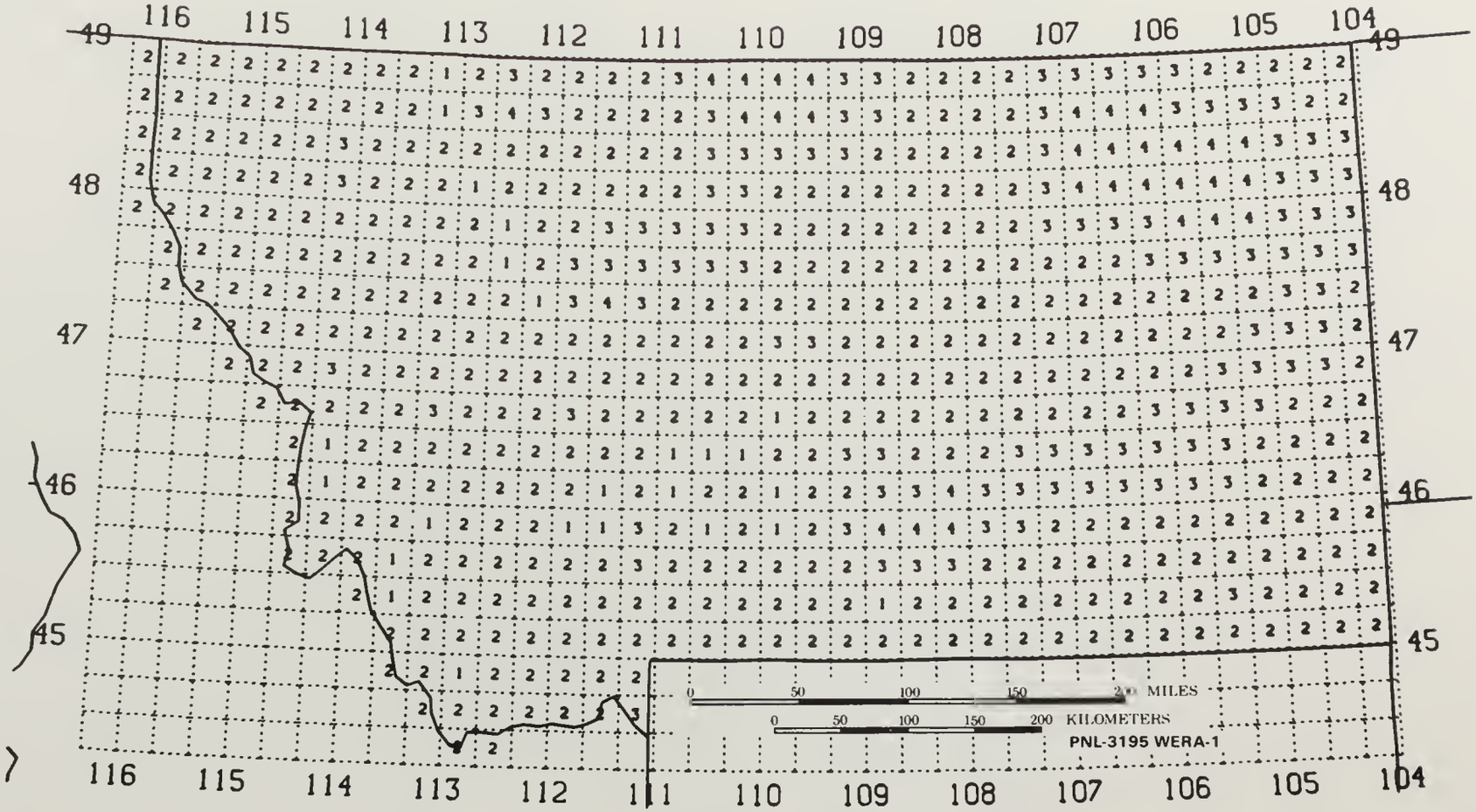
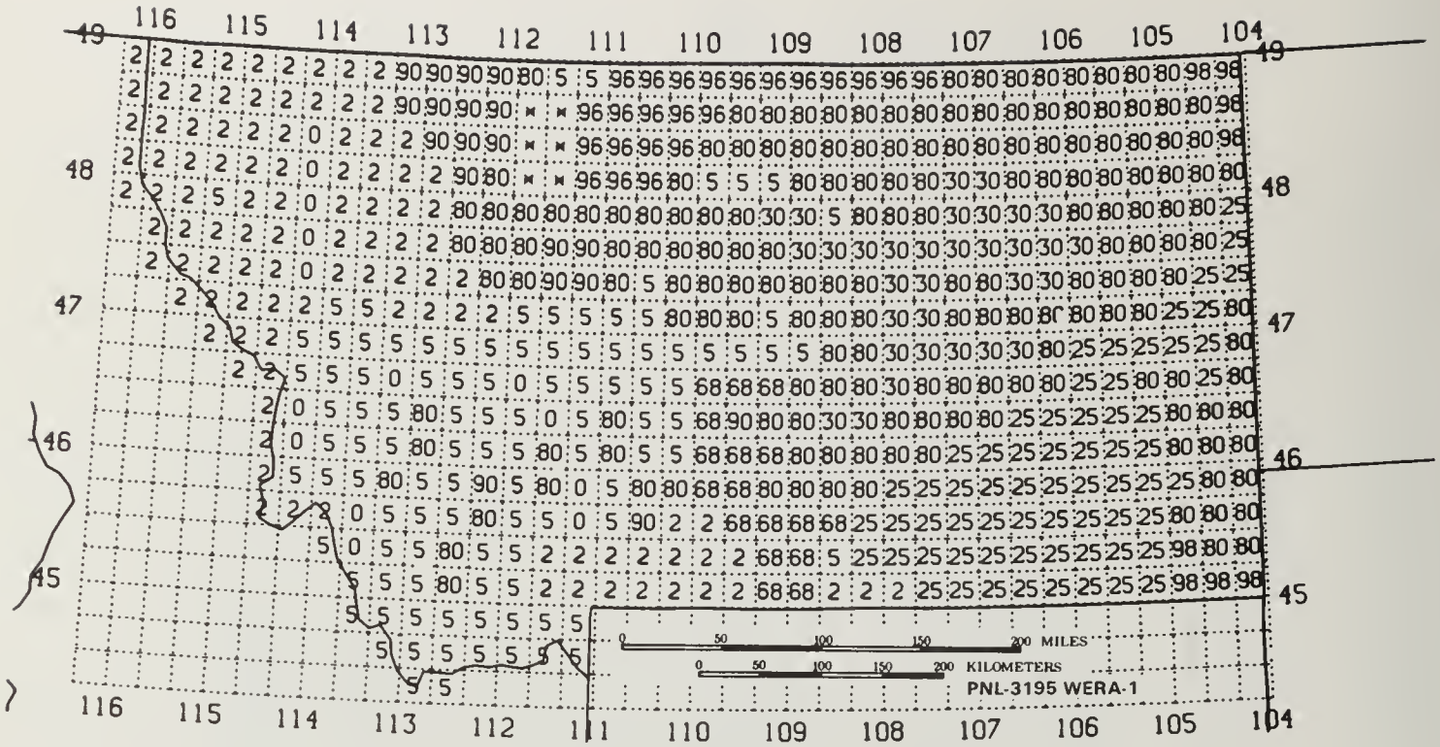


FIGURE 5.7. Certainty Rating of Montana Wind Resource

CERTAINTY RATING LEGEND

Rating	Definition
1	The lowest degree of certainty. A combination of the following conditions exists: 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	A low-intermediate degree of certainty. One of the following conditions exists: 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	A high-intermediate degree of certainty. One of the following conditions exists: 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.

Class 2



Class 3

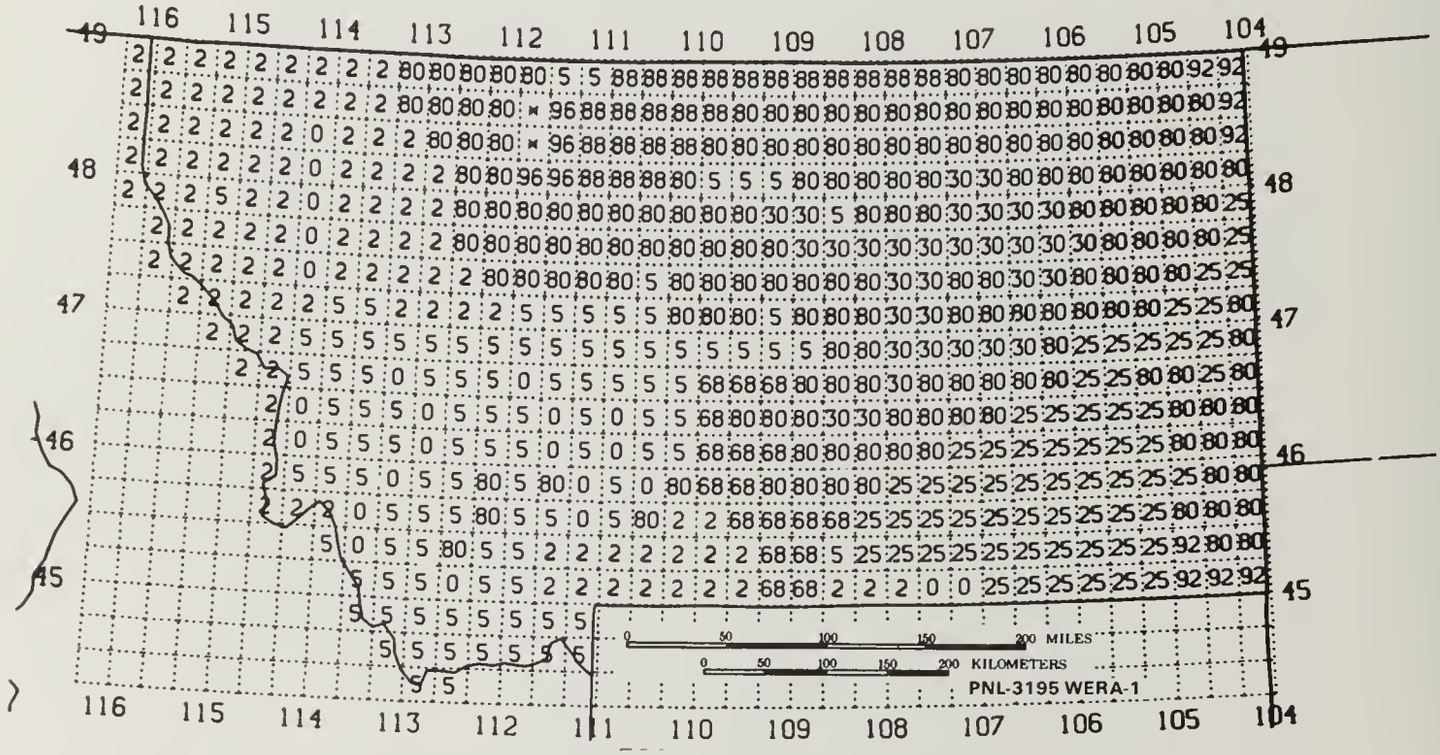
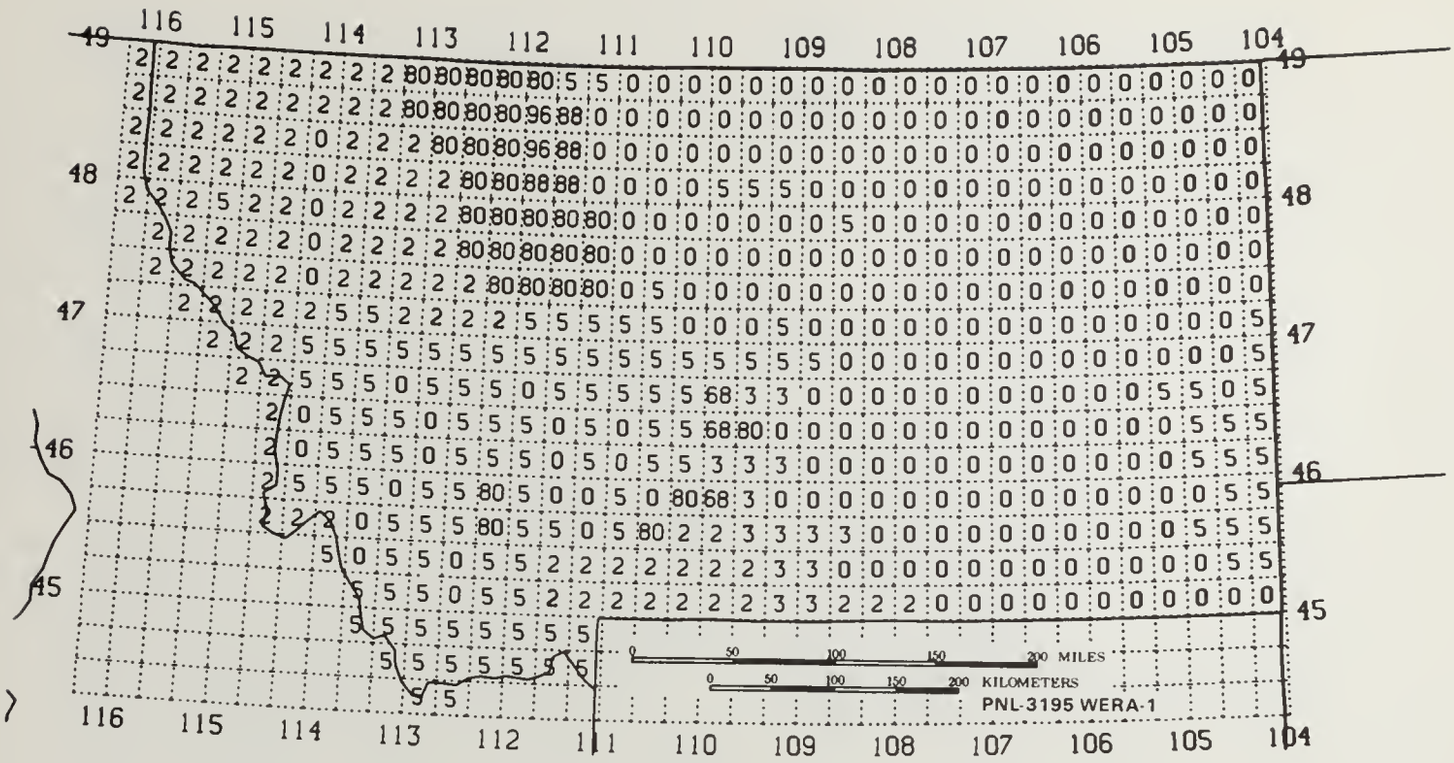


FIGURE 5.8. Areal Distribution of Wind Resource in Montana (Power Classes 2 and 3); Percent of Land Area With or Exceeding Power Class Shown. An asterisk denotes 100%.

Class 4



Class 5

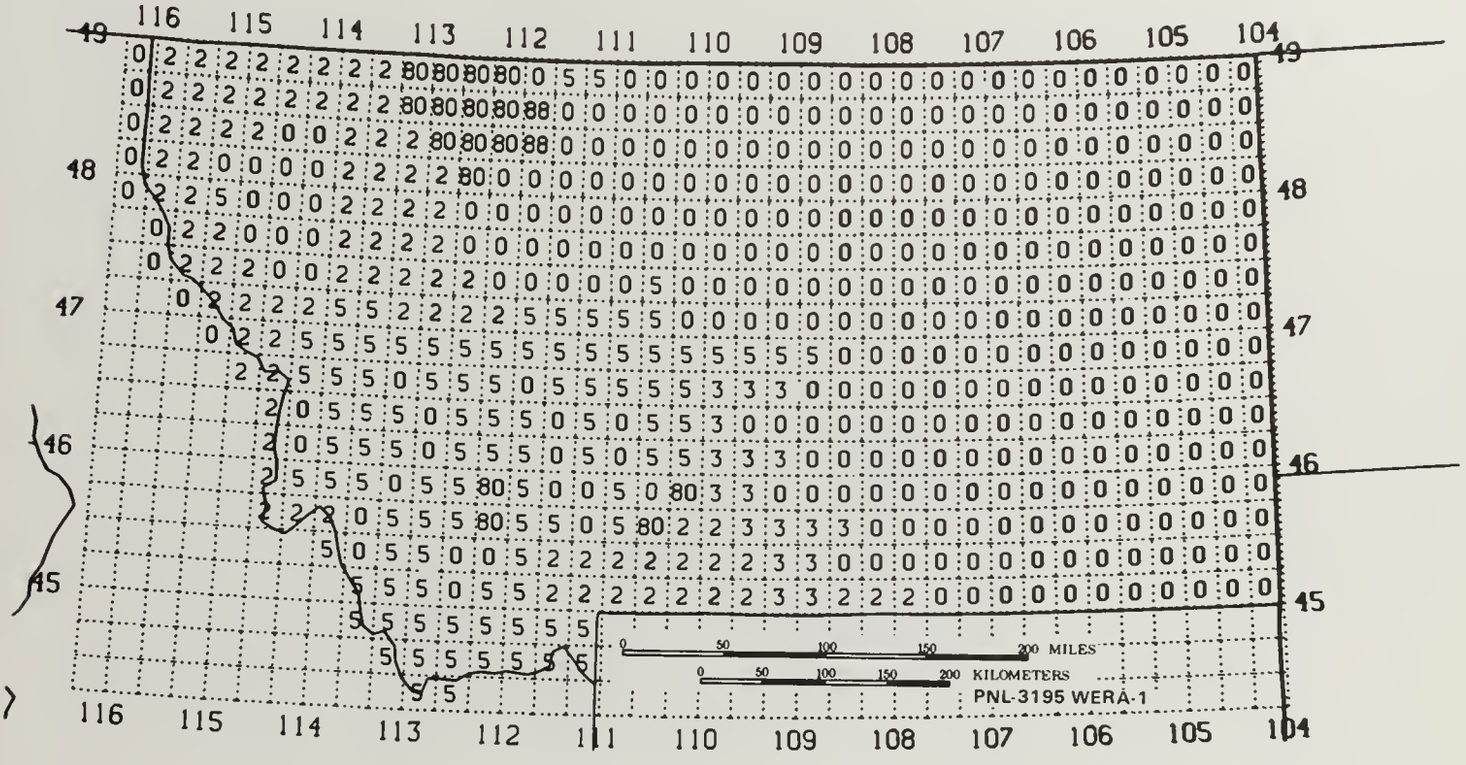


FIGURE 5.8 (Continued). Areal Distribution of Wind Resource in Montana (Power Classes 4 and 5); Percent of Land Area With or Exceeding Power Class Shown.

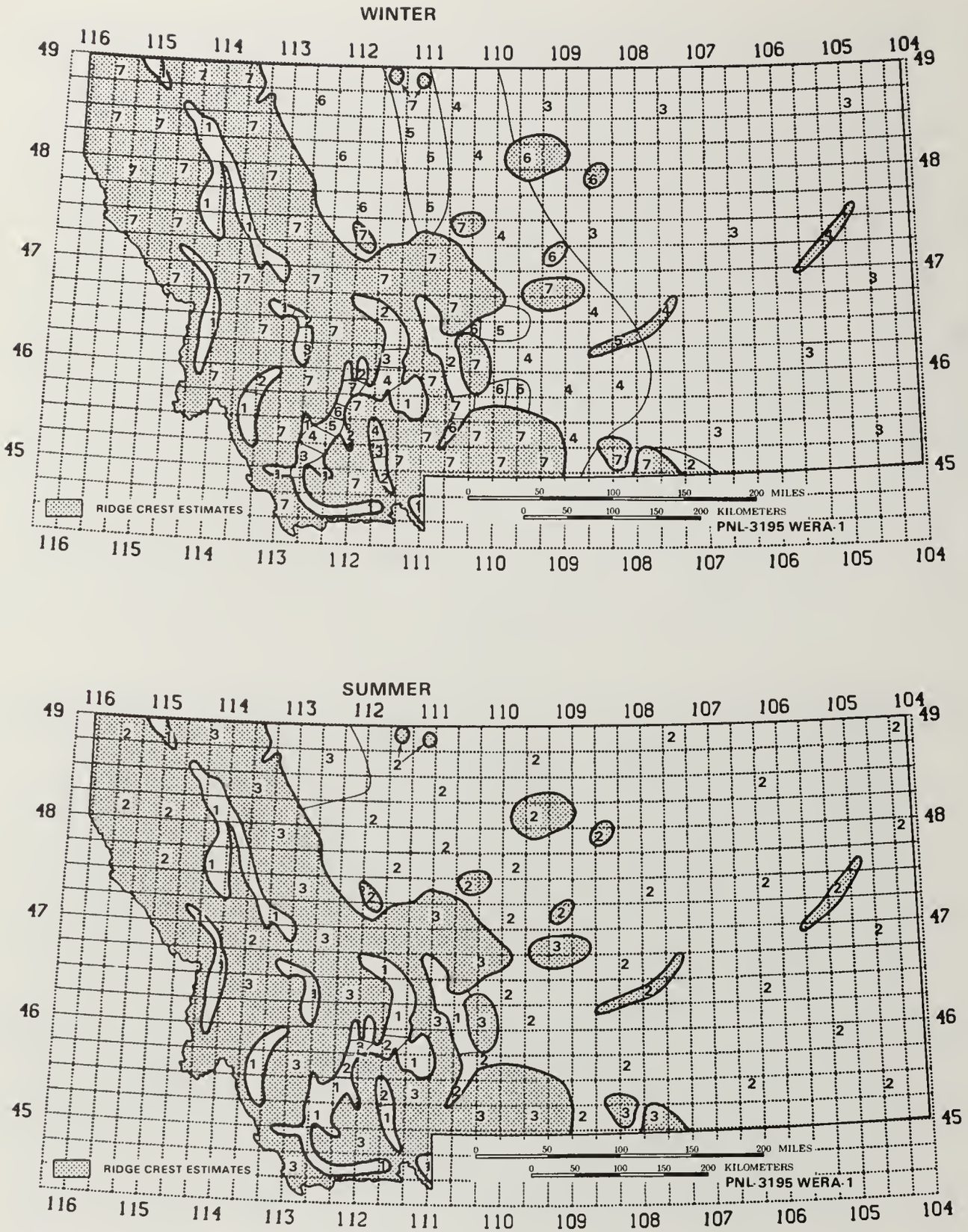
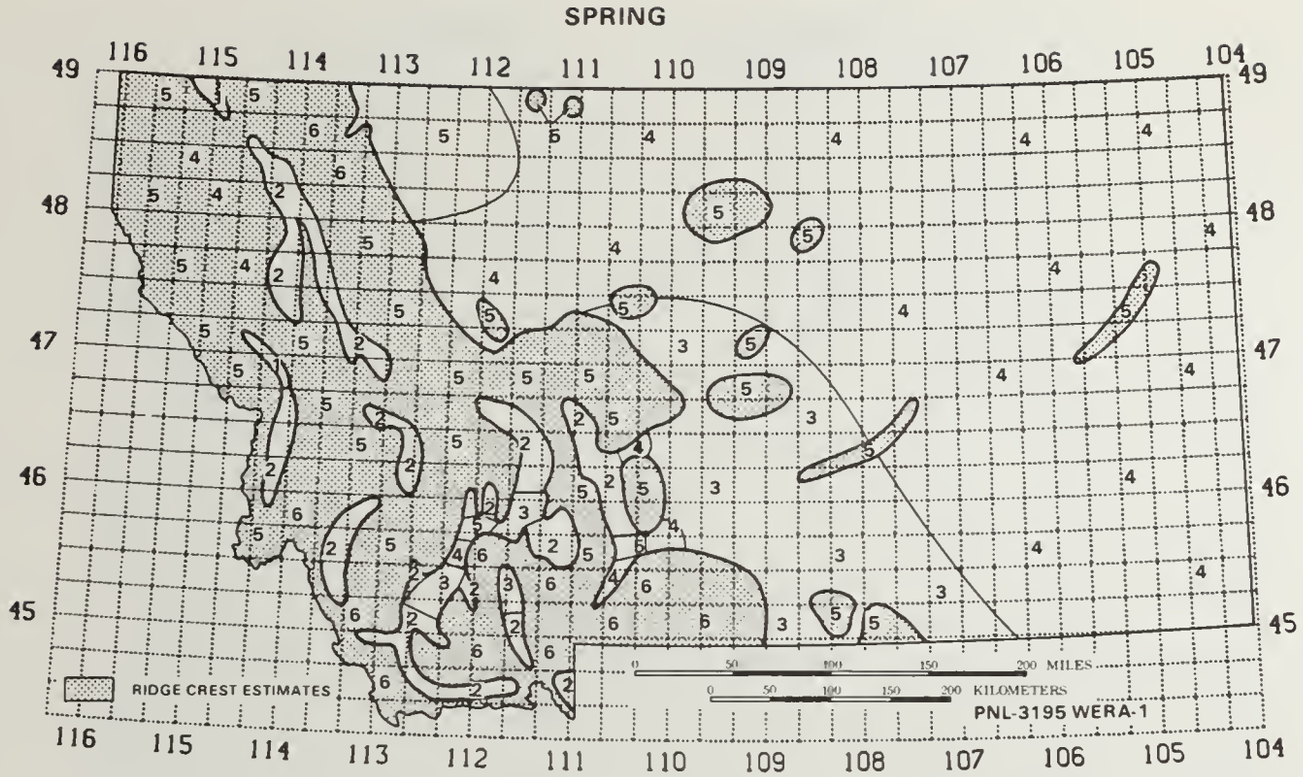


FIGURE 5.9. Seasonal Average Wind Power in Montana (Winter, Summer)



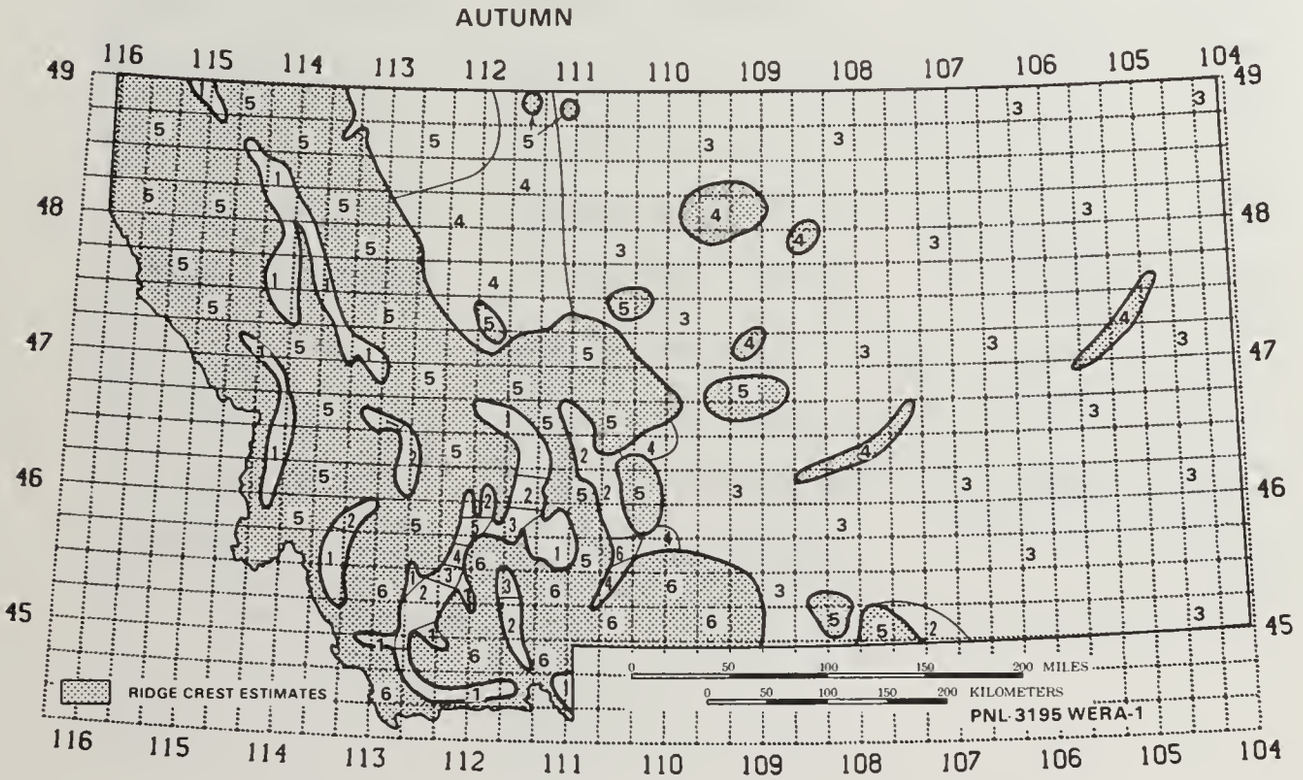


FIGURE 5.9 (Continued). Seasonal Average Wind Power (Spring, Autumn)

TABLE 5.2. Montana Stations with Graphs of the Wind Characteristics

Station	Station Name[a]	Latitude, Degrees North	Longitude, Degrees West	Elevation of Station, m	Period of Record, Month/Year	Anemometer Height, m	Annual Average Wind Speed, m/s			Annual Average Wind Power, watts/m²		
							At Anemometer Height, m	At 10 m	At 50 m	At Anemometer Height, m	At 10 m	At 50 m
Billings, Montana	Billings Logan International Airport	45.80	108.53	1092	06/58-12/76	7.6	5.3	5.5	6.9	139	156	311
Bozeman, Montana	Bozeman Airport	45.78	111.15	1362	04/51-12/54	13.1	3.7	3.5	4.5	71	63	126
Butte, Montana	Silver Bow County Airport	45.95	112.50	1689	01/48-12/59	18.0	3.7	3.4	4.3	90	70	139
Cut Bank, Montana	Cut Bank Airport	48.60	112.37	1174	10/59-12/76	6.1	5.7	6.1	7.7	230	284	567
Dillon, Montana	Beaverhead County Airport	45.25	112.55	1592	10/63-12/67	6.4	4.2	4.5	5.7	85	103	205
Glasgow, Montana	Glasgow AFB	48.40	106.52	853	06/61-06/68	4.0	4.4	5.0	6.3	111	165	329
Glasgow, Montana	Glasgow International Airport	48.22	106.62	695	08/62-12/76	6.1	5.0	5.4	6.7	141	174	347
Glasgow, Montana	Glasgow WBO (City)	48.18	106.63	643	01/48-10/55	16.2	4.0	3.8	4.8	93	76	151
Great Falls, Montana	Malmstrom AFB	47.52	111.17	1056	03/58-11/65	4.6	3.9	4.4	5.6	97	136	270
Great Falls, Montana	Great Falls International Airport	47.48	111.37	1124	08/59-12/76	6.7	5.4	5.7	7.2	183	217	433
Havre, Montana	Havre City-County Airport	48.55	109.77	788	02/61-12/76	6.1	4.8	5.1	6.4	130	161	320
Havre, Montana	Havre WBO (City)	48.57	109.67	760	05/50-01/61	20.4	4.0	3.6	4.6	78	57	114
Lewiston, Montana	Lewiston Airport	47.05	109.45	1263	10/64-12/76	6.1	4.6	4.9	6.2	111	137	274
Livingston, Montana	Livingston Airport	45.67	110.53	1399	01/48-07/53	17.4	7.1	6.5	8.2	511	403	804
Miles City, Montana	Miles City Airport	46.43	105.87	802	01/53-12/76	12.2	4.7	4.5	5.7	118	108	216
Superior, Montana	Superior Airport	47.18	114.87	823	01/48-11/53	17.7	2.3	2.2	2.7	16	13	25
Whitehall, Montana	Whitehall CAA	45.82	112.20	1403	01/48-12/54	9.1	6.0	6.0	7.6	327	340	677

[a]CAA-Civil Aeronautics Administration Facility; AFB-Air Force Base; WBO-Weather Bureau Office.

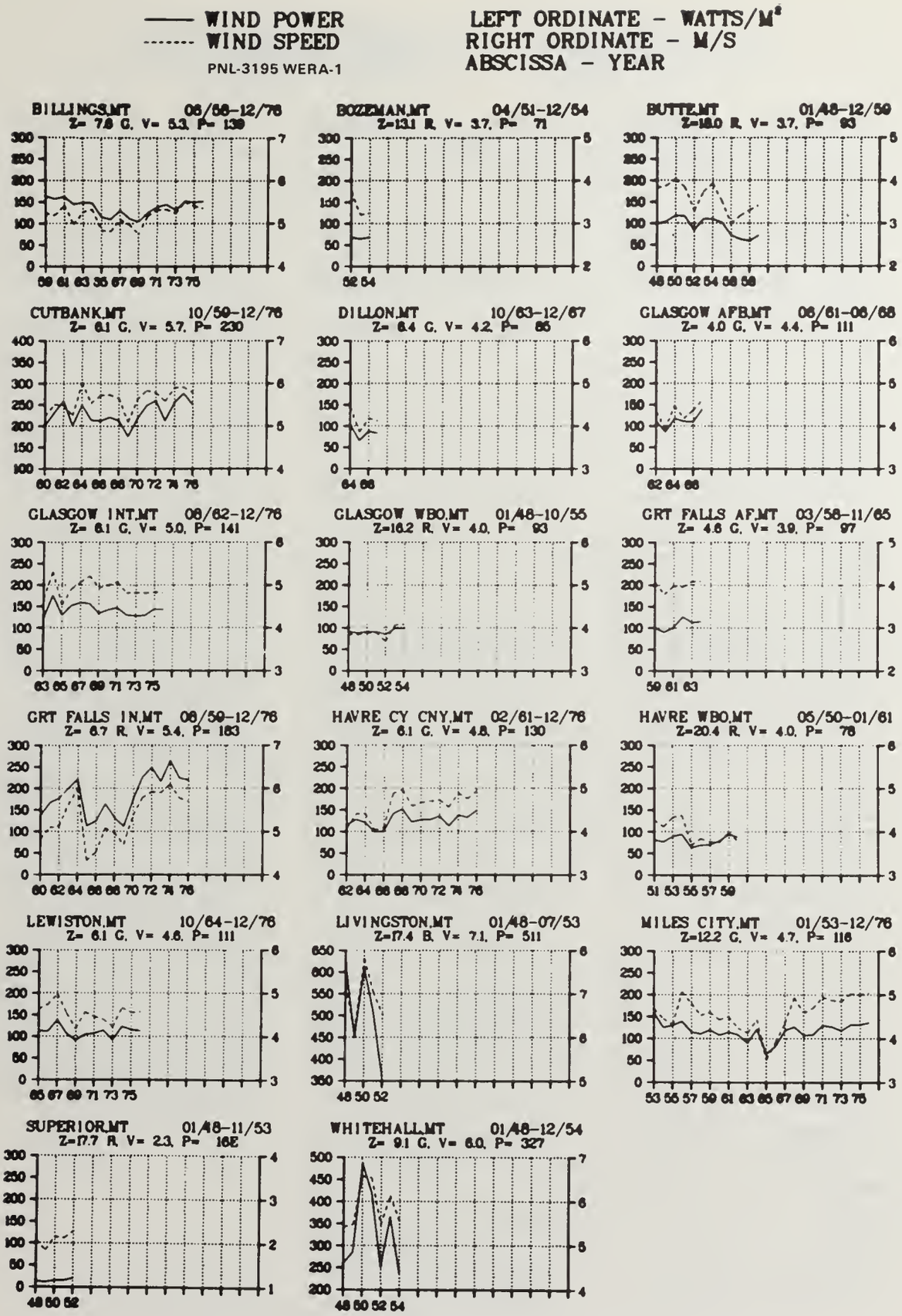


FIGURE 5.10. Interannual Wind Power and Speed for Montana

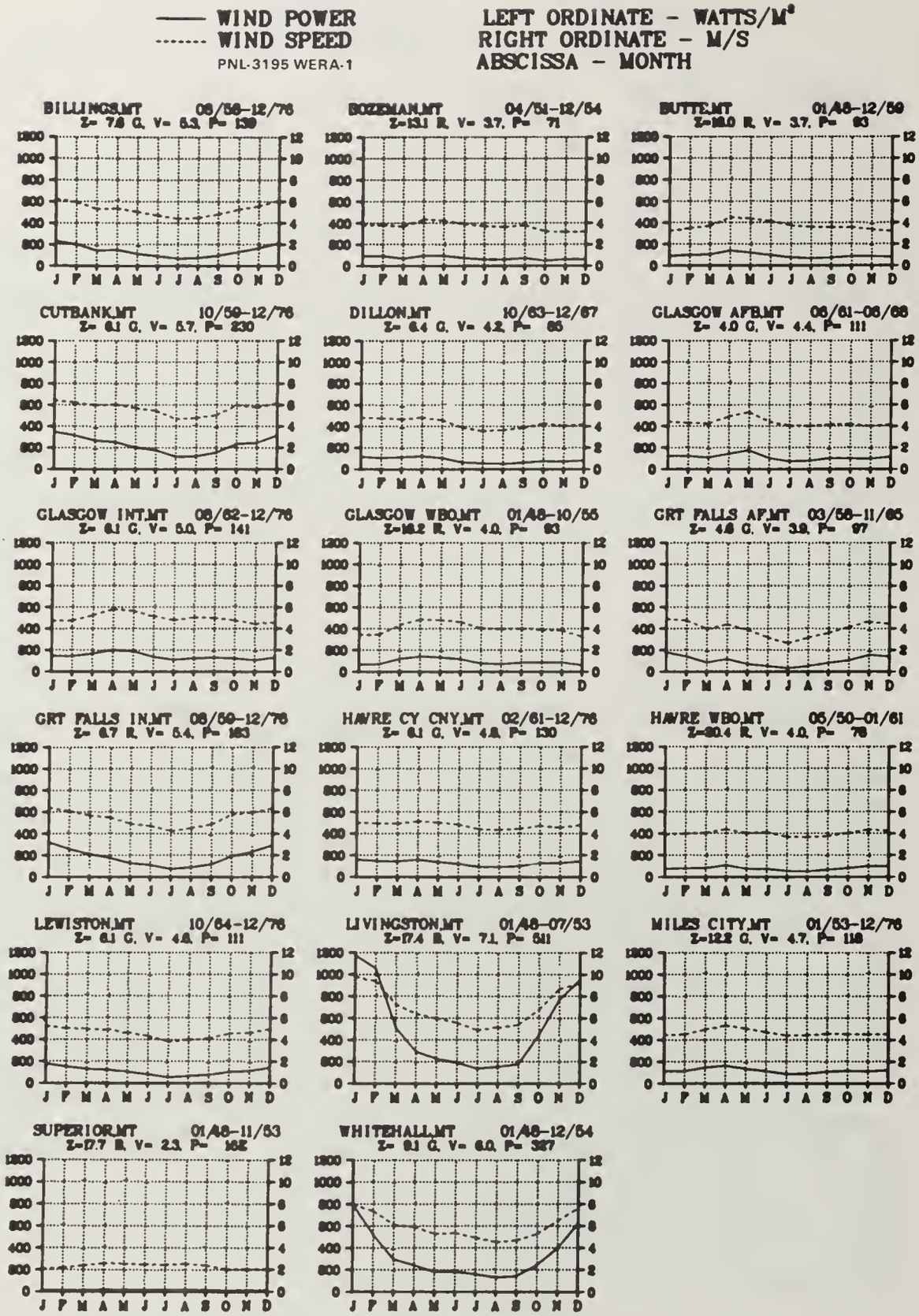


FIGURE 5.11. Monthly Average Wind Power and Speed for Montana

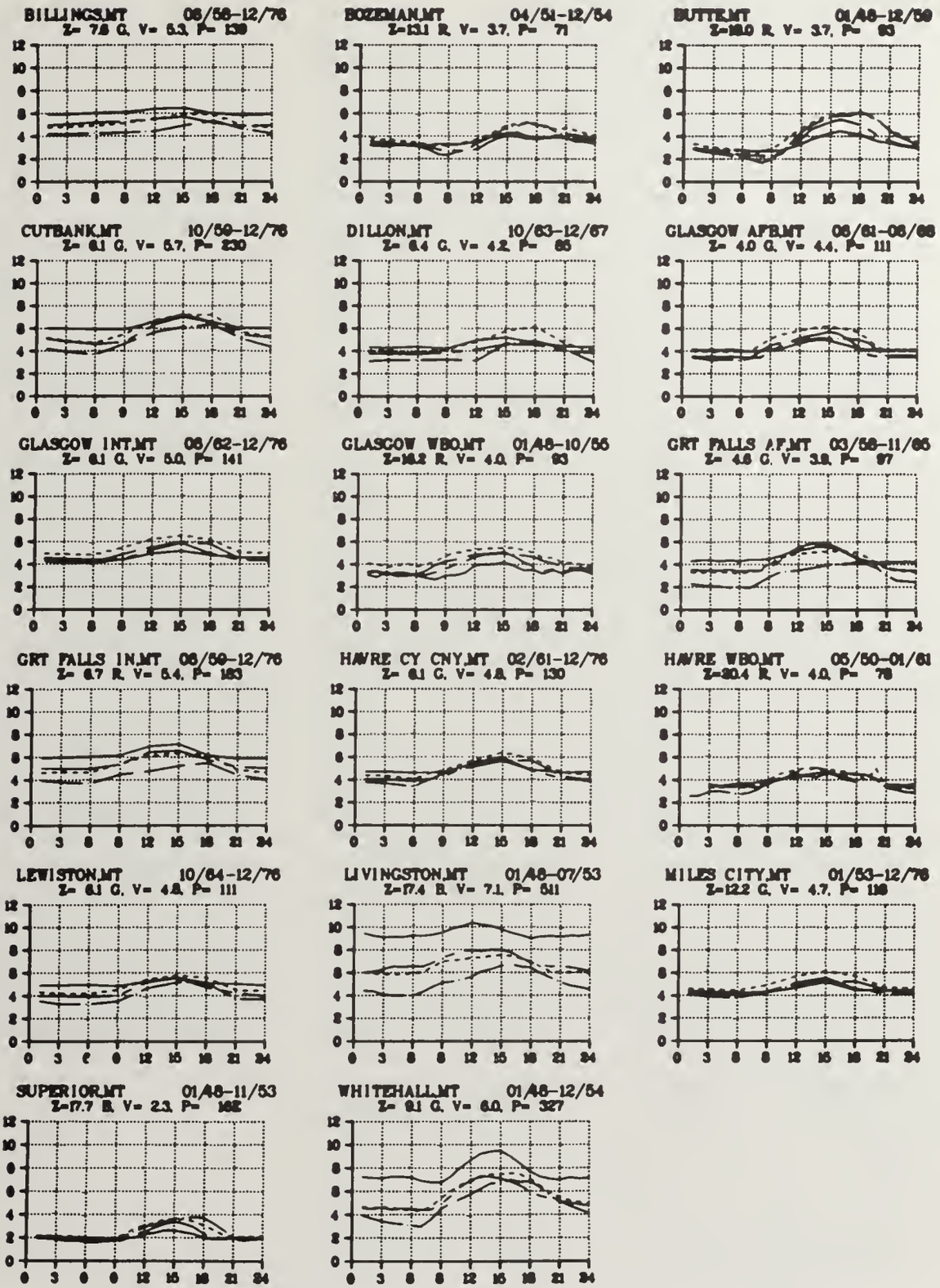


FIGURE 5.12. Diurnal Wind Speed by Season for Montana

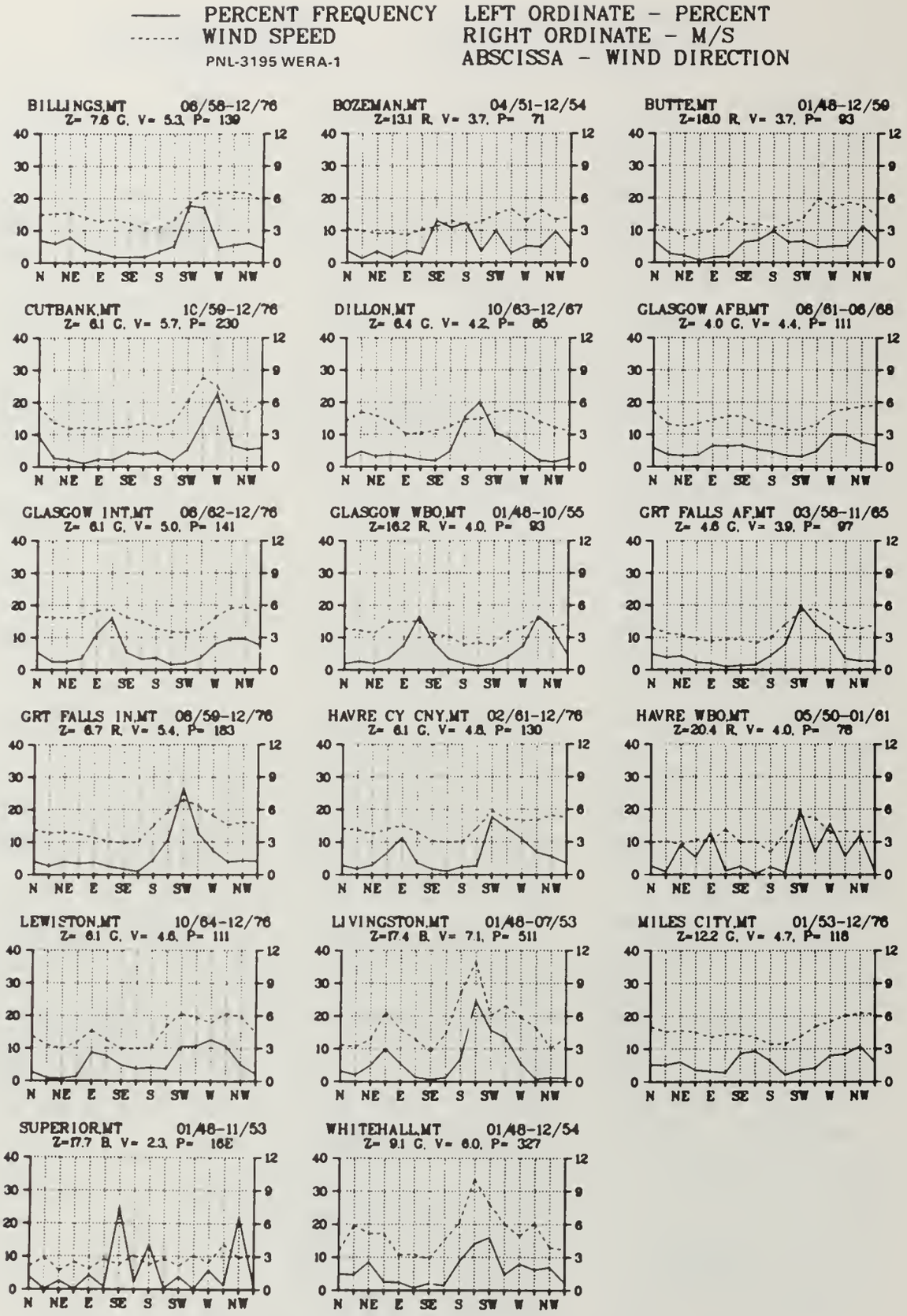


FIGURE 5.13. Directional Frequency and Average Speed for Montana

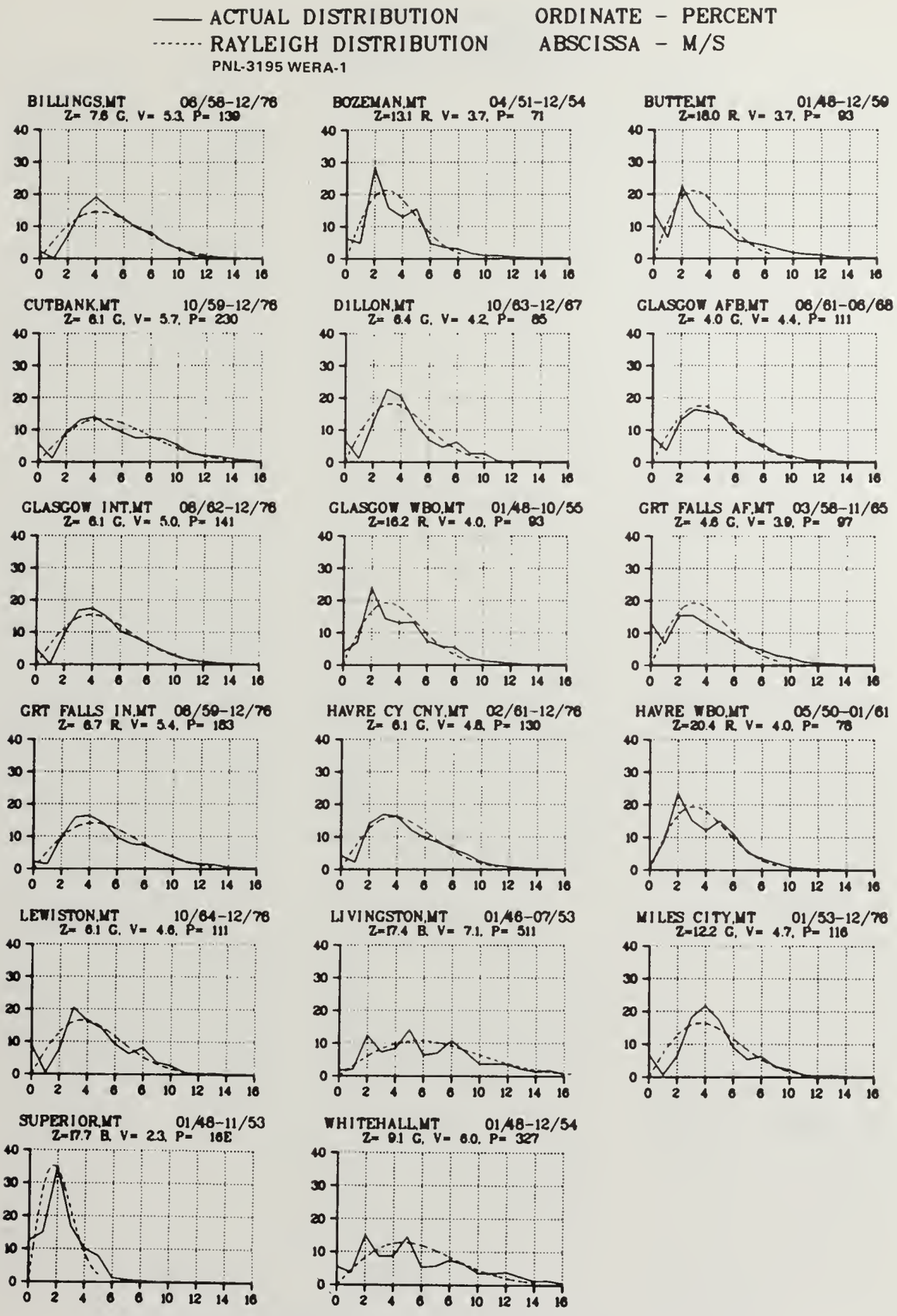


FIGURE 5.14. Annual Average Wind Speed Frequency for Montana

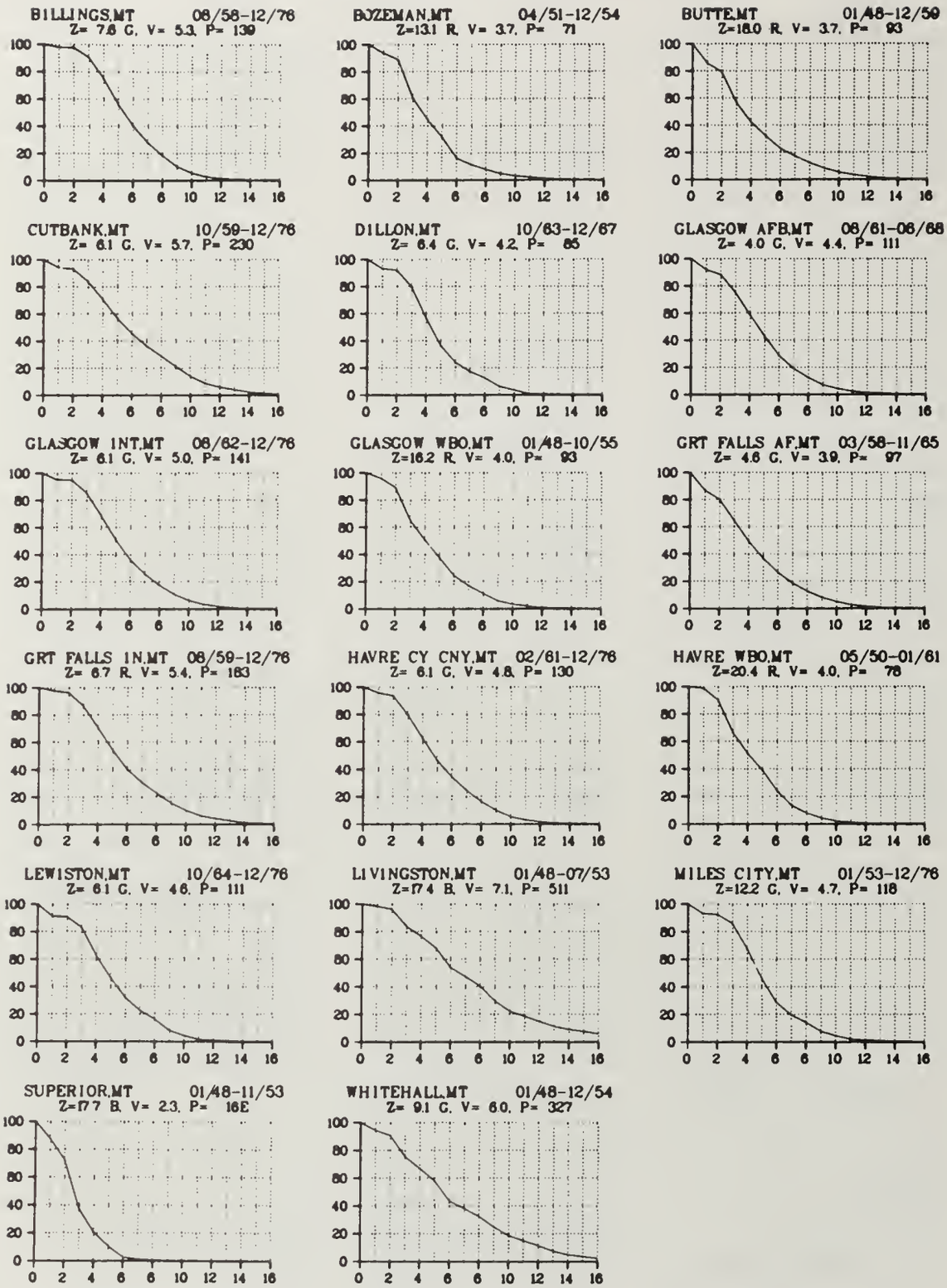


FIGURE 5.15. Annual Average Wind Speed Duration for Montana

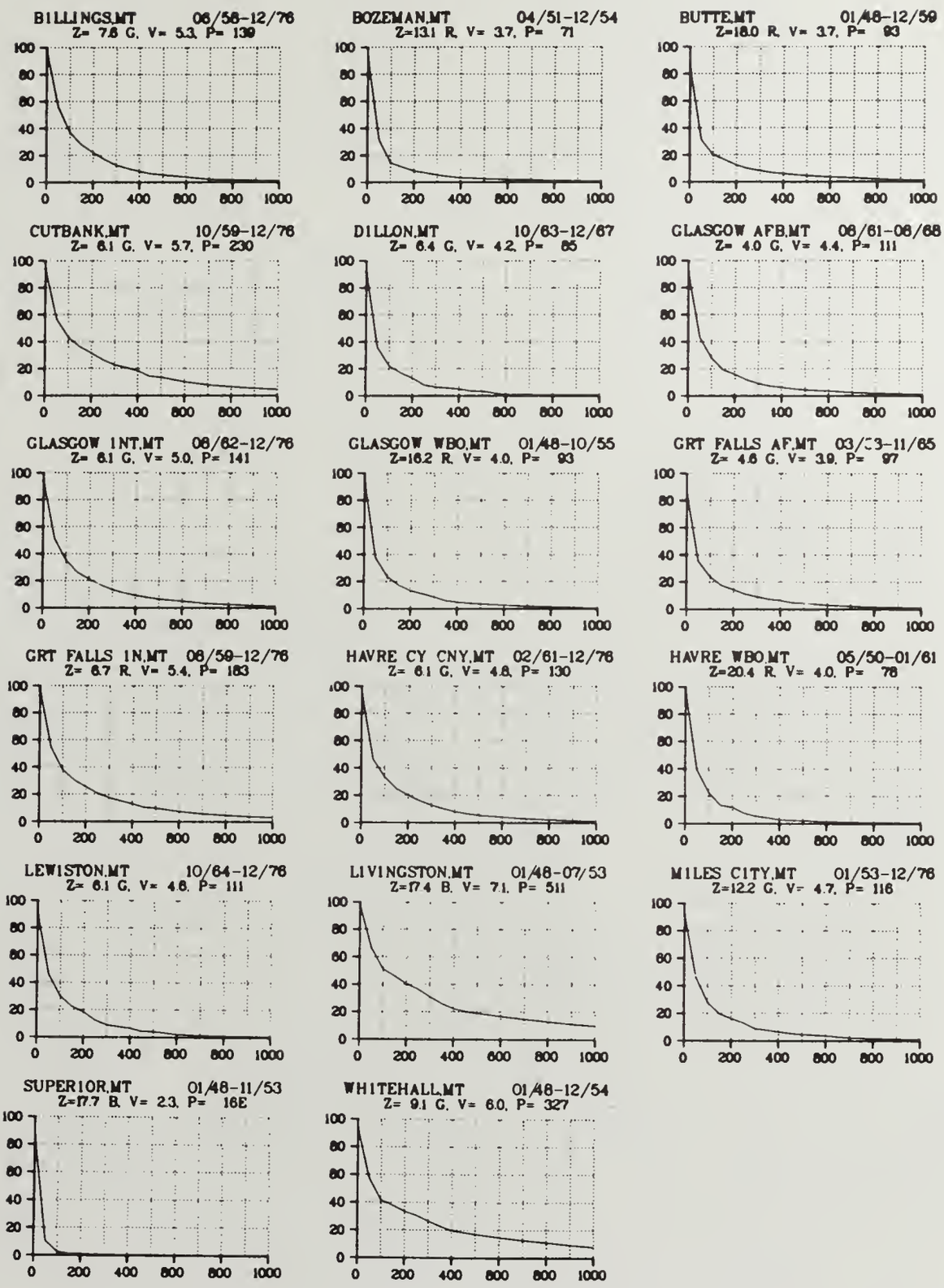


FIGURE 5.16. Annual Average Wind Power Duration for Montana

OREGON

CHAPTER 6: OREGON

Oregon, which had a population of 2,091,533 in 1970, covers an area of about 251,000 km^2 (96,981 mi^2). Most of the people in Oregon live in the western third of the state, primarily in the Willamette River valley (see Figure 6.1). Portland, with a population of over 350,000, is the largest city in Oregon and the second largest city in the Northwest. Much of eastern Oregon is sparsely populated. For example, Burns, one of the major towns in southeast Oregon, has a population of less than 4,000.

The Cascade Range, which extends north to south through the western third of the state (see Figure 6.2), is the dividing zone between a basically marine climate to the west and an arid climate to the east. A marine climate with moderate exists in the Willamette River valley, despite the presence of the Coast Range north of Roseburg, which has elevations of 600 to 1,200 m (2,000 to 4,000 ft). South of Roseburg, higher coastal mountains and less frequent storms (low pressure systems) cause the climate in the Grants Pass-Medford area to be more arid than in the Willamette River valley. Aside from the Willamette River valley, the western third of Oregon's terrain is mountainous (Figure 6.3). Eastern Oregon consists primarily of arid basins, valleys, and plains with mountains. The mountains of northeastern Oregon, such as the Blue, Wallowa, and Ochoco Mountains, are extensively forested, while the mountains in southeastern Oregon, such as Steens Mountain, are more sparsely forested and rise from open plains.

Wind data stations in Oregon, identified in Figures 6.4 and 6.5, are primarily found along the Oregon coast and along the interstate highway systems extending from Portland south to Medford and from Portland east to Ontario. Year-round wind data are very sparse in southeastern Oregon and the mountainous regions. Fire weather data (Figure 6.5) are fairly abundant in the forested mountains and in parts of southeastern Oregon, but only those stations for which more than 70% of the single daily observations during the fire weather season exceeded 3.5 m/s are shown in Figure 6.5. Of the 33 locations in Oregon for which summarized or digitized data were acquired from the National Climatic Center, only three stations with wind summaries were in southeastern Oregon. Nevertheless, heavy reliance must be placed on these few stations as being representative of most basin and valley areas in southeastern Oregon.

None of the six coastal stations with summarized or digitized data are representative of the wind power at exposed coastal and offshore sites. Therefore, summarized data from ships offshore and data collected at exposed coastal sites by Oregon State University and other organizations were primarily used in the evaluation of wind power at exposed coastal and offshore areas.

6.1 ANNUAL AVERAGE WIND POWER

The annual average wind power map for Oregon shows class 4 or higher wind power in the Columbia River corridor along the Washington border, the offshore and exposed sites along the Pacific coast, and the higher exposed mountain summits and ridge crests in the Cascade Mountains and the mountains of eastern Oregon (see Figure 6.6).

The Columbia River wind corridor straddles the Oregon-Washington state border from just east of Portland, Oregon to just west of Boardman, Oregon, which is about 75 km (45 mi) west of Pendleton. The Columbia River gorge between The Dalles and Portland provides a low-elevation passageway for intrusions of the continental air masses in the interior of the Columbia River basin east of the Cascade Mountains and the maritime air masses of the Pacific coast. Differences in the air density of continental and marine air masses cause exceptionally strong pressure gradients to develop across the Cascades that force the air to flow rapidly eastward or westward through the gorge. Summer winds blow eastward from the cool, dense maritime air west of the Cascades to the hot, less dense air in the Columbia Basin. In winter, the air in the Columbia Basin is cold and dense in comparison to the maritime air, and the wind blows westward through the gorge. The windiest locations change with the season and are near the downwind end of the gorge. Ridge crests and summits adjacent the gorge may have higher annual average wind power than areas in the gorge. For example, Mt. Augspurger, Washington, has a higher wind power than Cascade Locks, 20 km (12 mi) to the southwest.

The class 5 power estimates along the Oregon coast represent offshore areas and exposed coastal areas, e.g., open shorelines that are not sheltered from the prevailing winds. The winds may be accelerated around and over capes and headlands, where exposed areas can have class 6 or 7 power. The abrupt increase of surface roughness because of vegetation and topography inland from the coastline rapidly attenuates the wind resource landward of the coastline.

The Columbia River outlet, northwest of Astoria, frequently has strong easterly winds during the colder months and is estimated to have class 4 annual average power. Areas with class 3 annual power include the exposed summits and ridge crests in the Cascade Range and Coast Range that are generally 800 to 1,400 m (2,500 to 4,500 ft) in elevation, the La Grande valley wind corridor in northeast Oregon, and the eastern portion of the Columbia River corridor from near Arlington to Boardman.

The Willamette River valley has only class 1 power, except for areas located near the east end of corridors in the Coastal Range, such as Corvallis, and exposed hilltops and ridges in the Willamette River valley. During the summer months, marine air first intrudes into the Willamette River valley through these corridors in the Coast Range. There may be small areas with strong winds in these corridors, but existing data indicate that the power is class 2 near the corridor outlets.

Aside from the Columbia River and the La Grande corridors, the lowlands of eastern Oregon are estimated to have only class 1 and 2 wind power. However, other wind corridors with high wind power may exist in eastern Oregon that could not be identified with existing data. Open high plains and plateaus that are well exposed to the prevailing strong west-to-southwest winds are estimated to have higher wind power than lowlands such as the Harney Basin.

One year's data collected on ridge crests in the Warner Mountains indicate that these areas have approximately class 4 power. Based on this information and the estimated wind speeds aloft in southeastern Oregon, most of the exposed ridge crests and mountain summits are estimated to have at least class 4 power. However, locally higher wind power (classes 5, 6, or 7) may occur where the terrain slope and orientation accelerate the air flow.

In the Blue and Cascade Mountains, forested tablelands are estimated to have only class 1 and 2 power, since the high surface roughness caused by the forested terrain significantly reduces the power in the lowest 50 m, even in large clearings. For this reason, elevation cannot easily be related to wind power. For example, a site on a 1,000-m (3,000-ft) isolated bare ridge may have considerably greater power than a site on a 1,500-m (5,000-ft) forested tableland. The map values in mountainous terrain (shaded areas) only apply to exposed ridge crests and summits and not to high plateaus.

6.1.1 Certainty Rating of the Wind Resource

High certainty ratings of 4 are given only for the Willamette River valley, which is an area of low wind resource, and the Columbia Basin near Pendleton (Figure 6.7). No areas in Oregon have a large wind resource (class 4 or greater) and a high certainty. Some of the coastal areas with class 5 or 6 power estimates have high-intermediate certainty ratings. These are areas for which long-term data exist at exposed sites but where large spatial variability of the resource is expected. All other coastal areas have a low-intermediate certainty rating, as offshore marine data and limited coastal data were used in estimating the coastal wind resource.

Although the Columbia River corridor between Portland and Arlington has several wind data stations that indicate high wind power (class 4 or higher), certainty ratings of only 2 are assigned to these areas because of the extreme geographic variability of the wind resource. East of the Cascade Mountains, the Columbia River gorge opens into a tableland, but the southward extent of the high wind resource area from the Columbia River is uncertain.

The area around Portland has considerable wind data but was assigned a certainty rating of 3 because of the variability caused by the Columbia River corridor winds, especially during the winter season. Most of the Willamette River valley, extending south of Portland to Eugene, has a certainty rating of 4, as little variation is expected in this low wind resource area.

Much of the valley and basin area of southeastern Oregon has a low certainty rating of 1, due to the sparsity of the wind data, complexity of the terrain, and uncertain variability of the wind resource. Although only class 1 and 2 power is estimated for the basins and valleys in southeastern Oregon, some areas may have considerably greater wind power.

The certainty ratings of the mountain summit and ridge crest estimates (the shaded areas) are 2 in cells where the estimate is based only on upper-air data, and 3 in or near cells where the estimate is based on upper-air data supplemented with annual data collected at an exposed site.

6.1.2 Areal Distribution

The impact of the large expanses of class 1 and 2 wind power over the Harney

Basin and other sheltered areas in south-central Oregon is evident in the summary of the areal distribution of wind power classes given in Table 6.1. The large area contribution by power class 4 comes mostly from summits in the Cascade and Blue Mountains over 1,500 m (5,000 ft). Yet even here the fraction of cell area, shown in Figure 6.8, ranges from only 2 to 10%. The Columbia River gorge contributes only a small amount of area to the total for power class 4 through 7. The class 5 wind power along the coastal margin pertains only to a very narrow strip along the shoreline. The fractional contribution of the coastal areas to Oregon's areal wind power distribution is below the resolution of this analysis. However, the exposed coastal areas are likely to be easier to exploit than the mountainous areas with equivalent wind power class.

6.2 SEASONAL WIND POWER

Wind power maps for each season are shown on facing pages in Figure 6.9. Winter is the season of maximum wind power along the coastal areas, in the Willamette River valley, in the west end of the Columbia River gorge, in the La Grande area, and over mountain summits and ridge crests throughout the state. The season of highest wind power in the plains, valleys and basins east of the Cascade Range is spring. A summer wind power maximum is found at the east end of the Columbia River corridor and in corridors on the east slope of the Coast Range. A small area of autumn maximum wind power is located near Lakeview in south-central Oregon. Except for the eastern part of the Columbia River corridor and the southern Oregon coast, summer is generally the season of minimum wind power.

6.2.1 Winter

In the winter, class 6 and 7 wind power is estimated for exposed coastal and offshore areas, the western part of the Columbia River gorge, the La Grande area, and higher exposed ridge crests and summits in the Cascades and mountains of eastern Oregon. Small areas of high wind resource may exist in corridors and valley outlets in mountainous terrain where the winds are channeled or enhanced by nearby terrain. In winter, the class 6 wind energy at La Grande appears to be primarily due to strong south-to-southeast winds that are funneled and accelerated through the low gap south of La Grande. This gap connects two broad valleys and also provides a natural transportation corridor. The meteorological and topographical conditions that cause the high winds at the La Grande Airport may occur at various other areas in eastern Oregon where no data exist.

Strong easterly winds in the western end of the Columbia River gorge are usually associated with a relatively cold air mass over eastern Washington and exceptionally strong surface pressure gradients across the Cascades. However, ridge crest and mountain summit winds are usually class 1 under these weather conditions, as high pressure predominates the weather patterns aloft. The winds usually diminish significantly west of the gorge as they spread out into the Willamette River valley.

Class 1 and 2 power occurs in the Willamette River valley and in the lowlands of eastern Oregon, as cold stable air frequently settles in the basins and lowlands and inhibits the downward penetration of the generally strong winter winds aloft.

6.2.2 Spring

In the spring, class 4 or higher power is found along the Oregon coast, the mouth of the Columbia River, the Columbia River corridor, and higher exposed ridge crests and summits in the Cascades and mountains of eastern Oregon. In the spring, at least class 2 wind power occurs throughout most of the lowlands, basins, and plains of eastern Oregon. The west-to-southwest orientation of the Columbia River basin from The Dalles east to Pendleton provides nearly unobstructed flow to the prevailing westerly winds, such that areas of the Columbia River basin located outside the windy corridor (e.g., Pendleton) are estimated to have class 3 power.

6.2.3 Summer

In the summer, the southern Oregon coast and the central and eastern parts of the Columbia River corridor (from near Cascade Locks to around Arlington) have class 5 or higher power. The class 5 wind energy along the southern Oregon coast is associated with exceptionally strong surface pressure gradients. Since prevailing strong winds in summer are generally from the north, good coastal sites for summer wind power would be those well exposed to northerly winds. Wind power decreases from south to north along the Oregon coast. Wind corridors through the Coast Range are estimated to have class 2 or greater wind power, with the highest power expected at the eastern end of these corridors. Class 1 and 2 power occurs throughout most of the remaining areas of Oregon, except for some of the higher exposed summits and ridge crests in southeastern Oregon, which may have class 3 or higher power.

6.2.4 Autumn

In autumn, class 6 power is found in the western part of the Columbia River gorge,

and class 4 and 5 power is found along the Pacific Coast and higher ridge crests and mountain summits in the Cascades and mountains of eastern Oregon. In these areas, average wind power increases from September through November. Except for the mountainous areas, the wind power is primarily class 1 in autumn throughout most of eastern and western Oregon.

Lakeview, located in a broad valley in southcentral Oregon, is the only station in the Northwest that had an autumn maximum wind power based on 4 years of wind data. The autumn maximum appears to be caused by northerly drainage winds that reach their maximum intensity in October.

6.3 FEATURES OF SELECTED STATIONS

Table 6.2 gives the location and annual wind speed and power density of eleven stations in Oregon. Graphs of other features of the wind resource are shown in Figures 6.10 to 6.16. Two of these stations are near the Pacific Coast, three in the Willamette River valley, three in northeastern Oregon, one in southeastern Oregon, and one on a mountain summit in southwestern Oregon.

Eugene, located at the south end of the Willamette River valley, appears representative of exposed sites in the southern Willamette River valley. The site is an airport located 5 to 10 km (3 to 6 mi) northwest of Eugene near the center of the valley, which is about 25 km (15 mi) wide.

La Grande rests in a broad valley between the Blue and Wallowa Mountains in northeastern Oregon. The airport, located 5 to 10 km (3 to 6 mi) south of a gap through which winds are channeled and accelerated during the colder months, experiences frequent strong southerly winds. The town of La Grande, located 5 km (3 mi) northwest of the airport, appears to be partially sheltered from these strong southerly winds and is expected to have considerably lower wind energy than that of the airport.

Meacham, located on a forested plateau in the Blue Mountains in northeastern Oregon, is sheltered by the heavily forested environment. The anemometer is 8.8 m above ground and the annual average wind speed is only 2.9 m/s.

Newport, on the northcentral Oregon coast, has only 15 months of digitized data. The airport is about 1 km (0.5 mi) inland from the shore but is in a woodland environment. Therefore, average wind power at the airport is estimated to be one or more classes lower than at exposed coastal sites and offshore areas. However, the airport does appear to be representative of exposed inland sites in this coastal region.

North Bend is located on an inland bay near the southern Oregon coast. The airport is about 4 km (2.5 mi) inland from the shore, and is fairly well exposed to the prevailing north-to-northwest winds in summer, as the area north and west of North Bend is mostly sand dunes. But to the south, hilly forested terrain shields the station from the southerly winds, which are more frequent from October through April. Thus, the seasonal trend of wind power at North Bend has a summer maximum, whereas exposed coastal sites and off-shore areas along the southern Oregon coast experience maximum wind power in the winter.

Ontario is in eastern Oregon, near the Idaho border at the western end of the Snake River plain. The town and airport are partially sheltered by nearby hills and ridges that are 200 to 300 m (700 to 1,000 ft) higher in elevation.

Pendleton is located in the southeastern part of the Columbia Basin in northeastern Oregon. The Blue Mountains rise abruptly 15 to 25 km (10 to 15 mi) to the east and south. The airport appears well exposed to the prevailing westerly winds. However, the town of Pendleton is located in a shallow valley about 130 m (430 ft) lower than the airport and is expected to have lower wind power than the airport.

Portland rests in the northern end of the Willamette River valley near the confluence of the Willamette and Columbia Rivers. The airport is located along the Columbia River north of the city. The large geographic variability of the wind resource at the western end of the Columbia River gorge may make the wind characteristics of the airport unrepresentative of much of the Portland area, especially during the winter months.

Rome is located in the sparsely populated southeastern part of Oregon. The airport is located in a basin about 30 km (20 mi) southwest of the town. The basin is aligned southwest to northeast and contains scattered hills. Only 1 year's digitized data are available for Rome.

Sexton Summit is located on the peak of one of the minor mountains in the Coast Range of southwestern Oregon. The terrain is covered with coniferous timber and slopes away steeply in all directions to valleys below. The station is well exposed to the free circulating air aloft.

Troutdale is located about 15 km (10 mi) west of the west entrance to the Columbia

River gorge. During the colder months, winds at this station are influenced by the strong easterly winds blowing out of the Columbia River gorge.

6.3.1 Interannual Wind Power and Speed

Six stations have selected periods of record of 10 years or more during which the anemometer was not moved (Figure 6.10). During 1976--a drought year--the wind power in comparison to the long-term mean was low at all five stations that had records through 1976. Sexton Summit appears to have the largest interannual variability; the highest annual powers were approximately double the lowest annual powers. Some of the stations show long-term trends that must be interpreted with caution, e.g., the wind speeds show a gradual decrease with time at Meacham and a gradual increase with time at North Bend.

6.3.2 Monthly Average Wind Power and Speed

Largest monthly and seasonal variations occur at La Grande, Newport, Sexton Summit, and Troutdale (Figure 6.11). Both Troutdale and La Grande are located downwind of gaps or corridors where winter winds are funneled and enhanced. Sexton Summit is well exposed to the free air winds aloft, which are strongest in the winter. At Newport, the influence of coastal winter storms appears as a winter maximum. As discussed earlier, the summer maximum at North Bend is probably not typical of exposed coastal sites and offshore areas that have a winter wind power maximum. At Rome, the 1 year's data indicate a winter maximum. However, this is not consistent with other basin and plains stations with long-term records in southeastern Oregon (e.g., Burns and Ontario) and southwestern Idaho (e.g., Boise and Mountain Home) that indicate a distinct spring maximum. One year's data may not be reliable in determining seasonal trends.

6.3.3 Diurnal Wind Speed by Season

The eleven stations presented for Oregon show an interesting variety of diurnal trends (Figure 6.12). Except at Sexton Summit, highest mean daily wind speeds occur during the afternoon and early evening, depending on the season. Highest mean speeds are usually in the early afternoon (1300 to 1500 LST) in the winter and in the late afternoon or early evening (1600 to 1900 LST) in the summer. Greatest diurnal variations usually occur in the summer, the least in the winter.

Diurnal variations exceeding 3 m/s in the summer are evident at the two coastal stations (Newport and North Bend). The strong temperature contrast between the cold coastal water and hot interior intensifies the surface pressure gradients and the wind speeds along the coast.

At Sexton Summit, the wind speeds are at a minimum near mid-day (1100 to 1400 LST) and a maximum between 2000 to 2400 LST, varying somewhat with the seasons. Diurnal variations at Sexton Summit are very small during the winter but quite large during the summer, with average summer speeds ranging from about 3 m/s at 1100 LST to about 7 m/s at 2000 LST.

Although Meacham is located on a forested plateau in the Blue Mountains, its diurnal trend is similar to that of most valley and plain stations in eastern Oregon and quite different from that of Sexton Summit. Extensive plateaus and uplands in mountainous terrain may create their own boundary layer and have maximum winds in the afternoon, whereas mountain summits and ridge crests that are exposed to the free air circulation may have maximum winds at night.

6.3.4 Directional Frequency and Average Speed

Prevailing surface wind directions throughout most of Oregon are strongly influenced by the terrain (Figure 6.13). Along the coast and in the Willamette River valley, e.g., at Eugene, North Bend, and Newport, prevailing winds are generally northerly in the summer and southerly in the winter. Portland and Troutdale have a maximum directional frequency from the east, which shows the strong influence of the Columbia River gorge winds.

At La Grande, the prevailing southerly winds of winter are stronger than the prevailing northwesterly winds of summer. At Pendleton and throughout most of the southern part of the Columbia Basin from Pendleton westward to The Dalles, prevailing strong winds are from the west to west-southwest. The secondary southeast maximum in the directional frequency at Pendleton represents the light drainage winds from the Blue Mountains.

6.3.5 Annual Average Wind Speed Frequency

Observer biases are apparent from the peaks at 2, 5, and 8 m/s (5, 10, and 15 knots) in the distributions for La Grande, Newport, Ontario, Rome, and Troutdale, which had periods of record in the 1940s and 1950s (Figure 6.14). Stations with more recent records show little evidence of this observer bias. For example, at Sexton Summit, where records are automated, the frequency distribution is very smooth. Moreover, the Rayleigh distribution approximates the actual annual average frequency distribution very well at Sexton Summit.

6.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 6.15 and 6.16. Abrupt changes in the slope of the duration curves correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

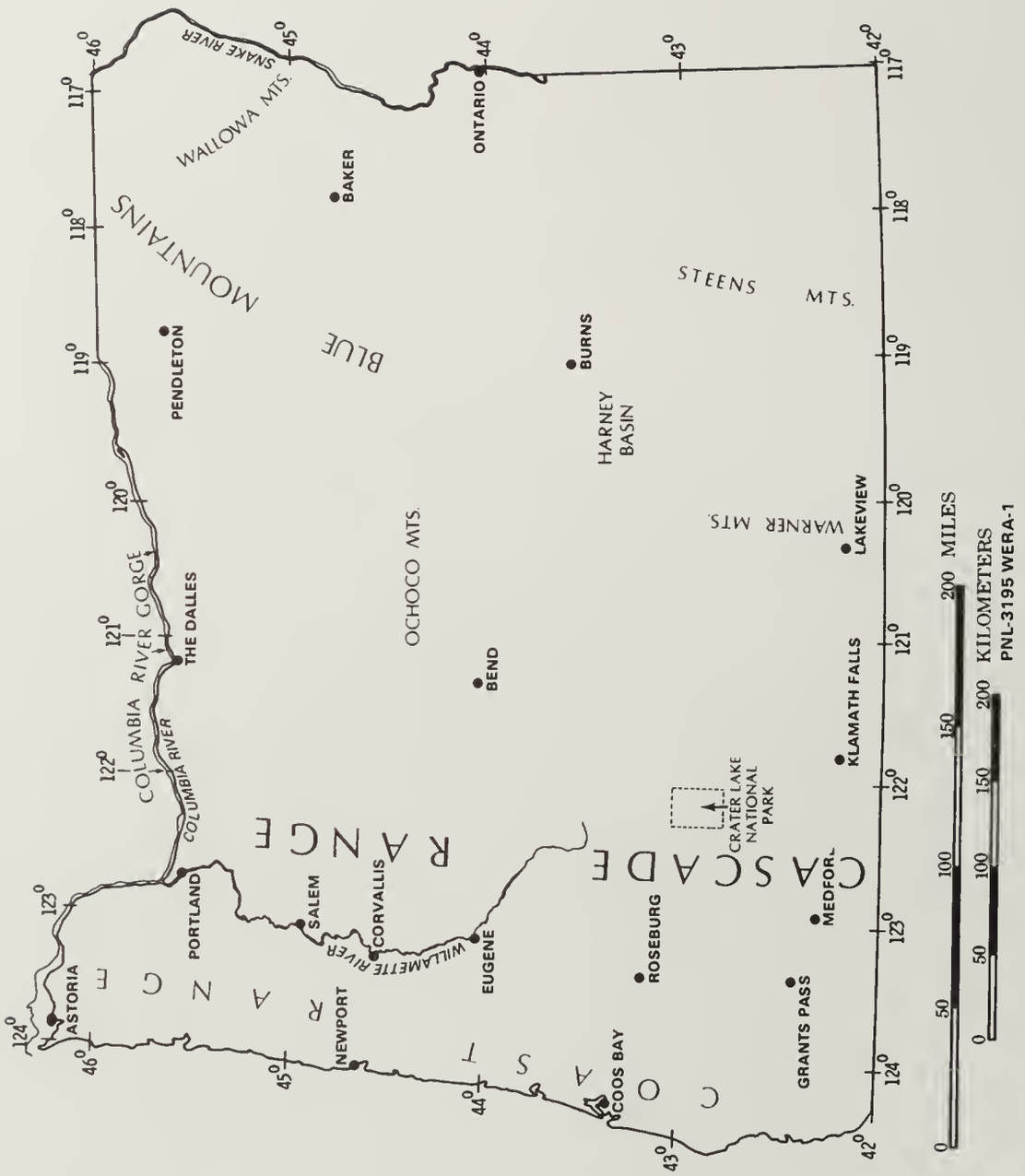


FIGURE 6.1. Geographic Map of Oregon

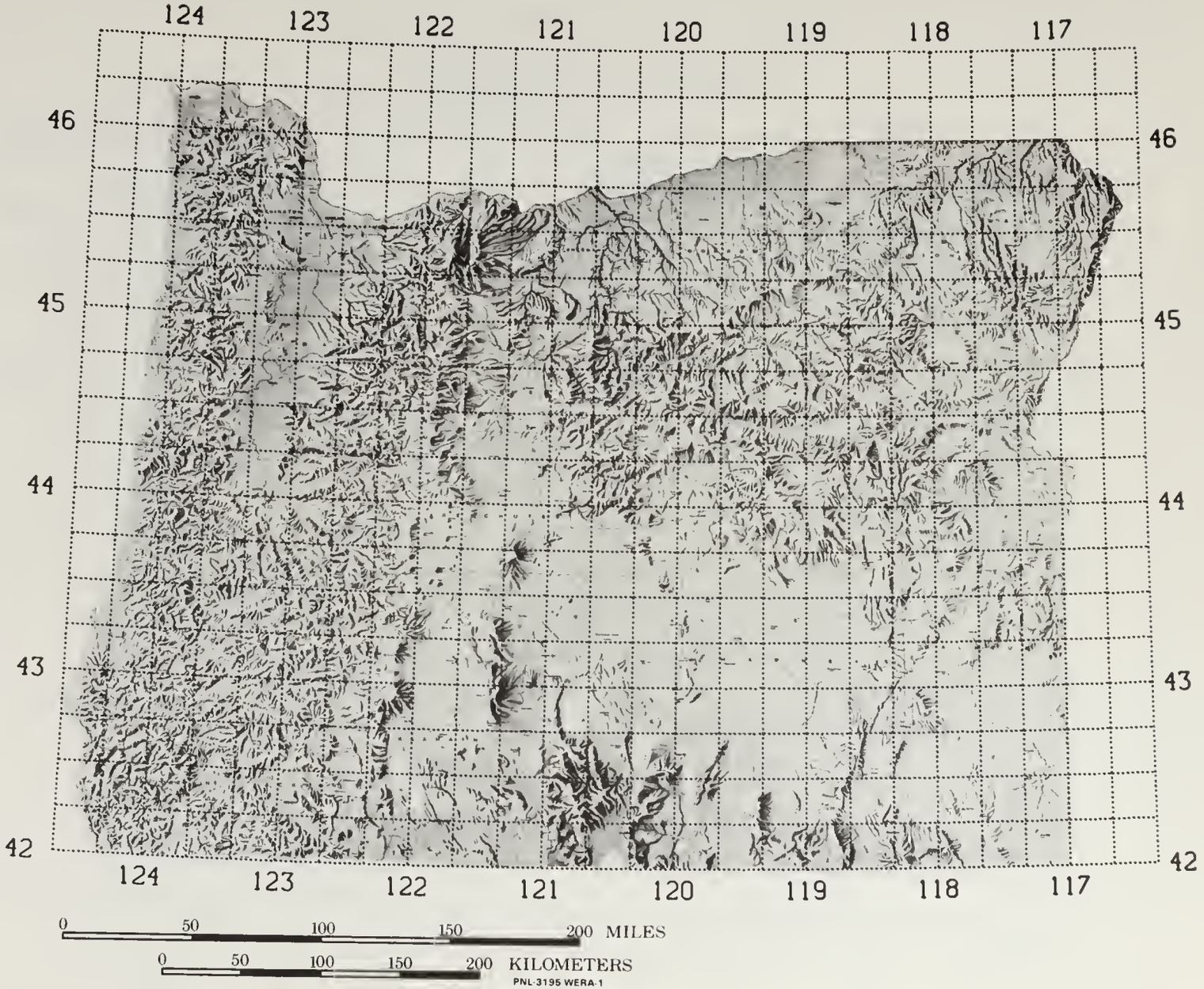


FIGURE 6.2. Topographic Map of Oregon

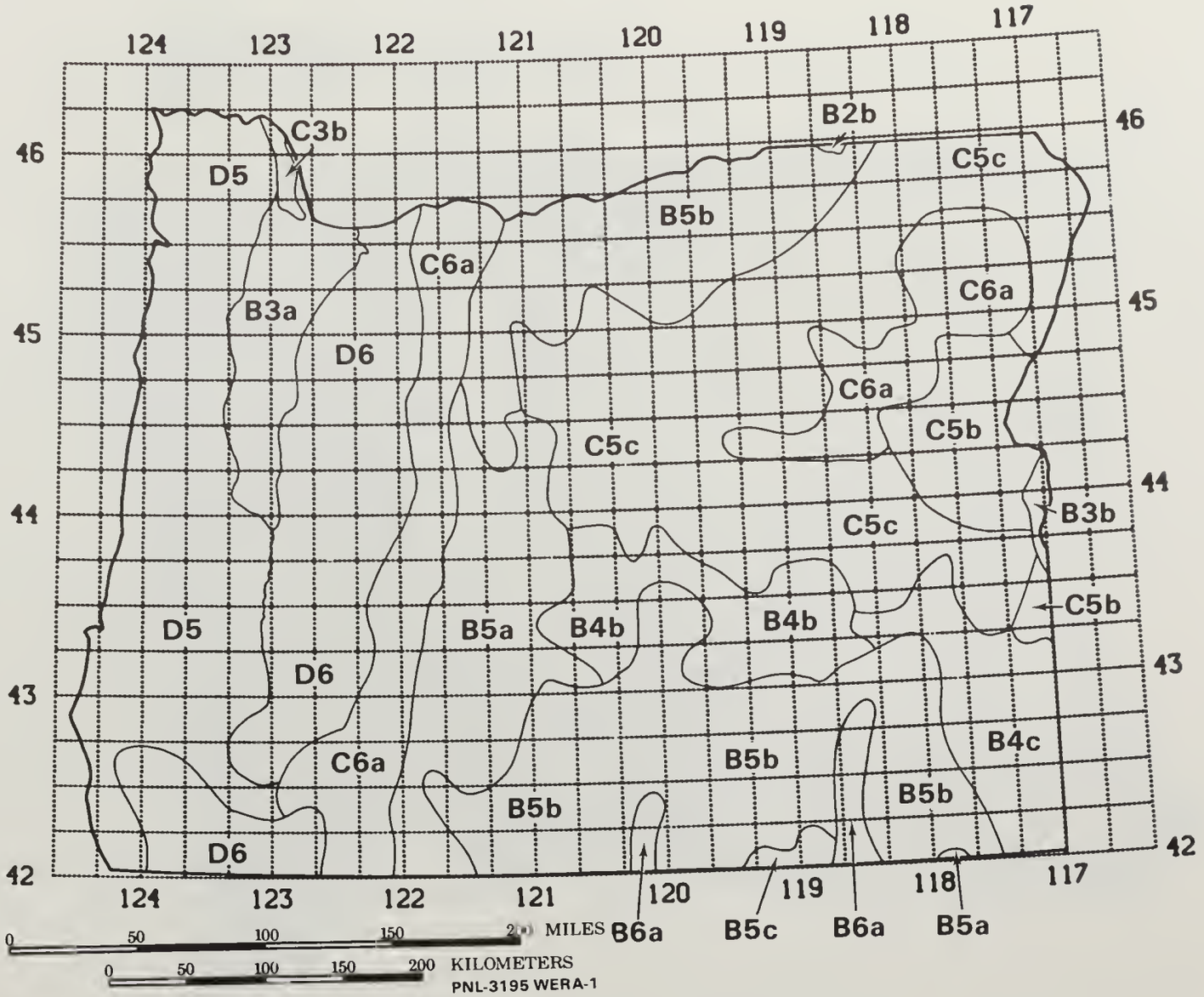


FIGURE 6.3. Land-Surface Form Map for Oregon

LAND-SURFACE FORM LEGEND

PLAINS

A1	FLAT PLAINS
A2	SMOOTH PLAINS
B1	IRREGULAR PLAINS, SLIGHT RELIEF
B2	IRREGULAR PLAINS

PLAINS WITH HILLS OR MOUNTAINS

A,B3a,b	PLAINS WITH HILLS
B4,a,b	PLAINS WITH HIGH HILLS
B5a,b	PLAINS WITH LOW MOUNTAINS
B6a,b	PLAINS WITH HIGH MOUNTAINS

OPEN HILLS AND MOUNTAINS

C2	OPEN LOW HILLS
C3	OPEN HILLS
C4	OPEN HIGH HILLS
C5	OPEN LOW MOUNTAINS
C6	OPEN HIGH MOUNTAINS

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

TABLELANDS

B3c,d	TABLELANDS, MODERATE RELIEF
B4c,d	TABLELANDS, CONSIDERABLE RELIEF
B5c,d	TABLELANDS, HIGH RELIEF
B6c,d	TABLELANDS, VERY HIGH RELIEF

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

A	>80% OF AREA GENTLY SLOPING
B	50-80% OF AREA GENTLY SLOPING
C	20-50% OF AREA GENTLY SLOPING
D	<20% OF AREA GENTLY SLOPING

LOCAL RELIEF (2nd LETTER)

1	0 TO 30m (1 TO 100 ft)
2	30 TO 90m (100 TO 300 ft)
3	90 TO 150m (300 TO 500 ft)
4	150 TO 300m (500 TO 1000 ft)
5	300 TO 900m (1000 TO 3000 ft)
6	900 TO 1500m (3000 TO 5000 ft)

PROFILE TYPE (3rd LETTER)

a	>75% OF GENTLE SLOPE IS IN LOWLAND
b	50-75% OF GENTLE SLOPE IS IN LOWLAND
c	50-75% OF GENTLE SLOPE IS ON UPLAND
d	>75% OF GENTLE SLOPE IS ON UPLAND

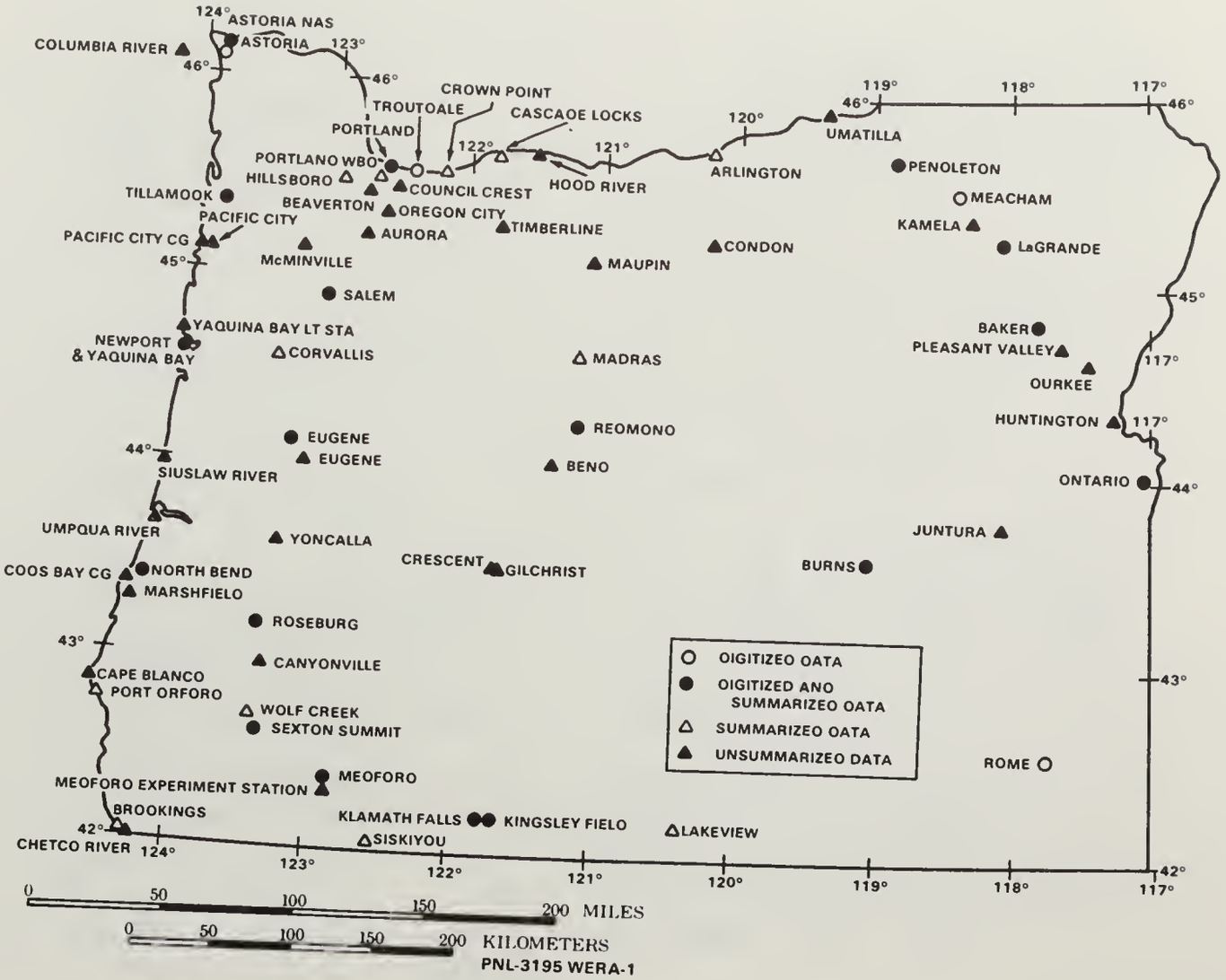


FIGURE 6.4. NCC Station Locations in Oregon

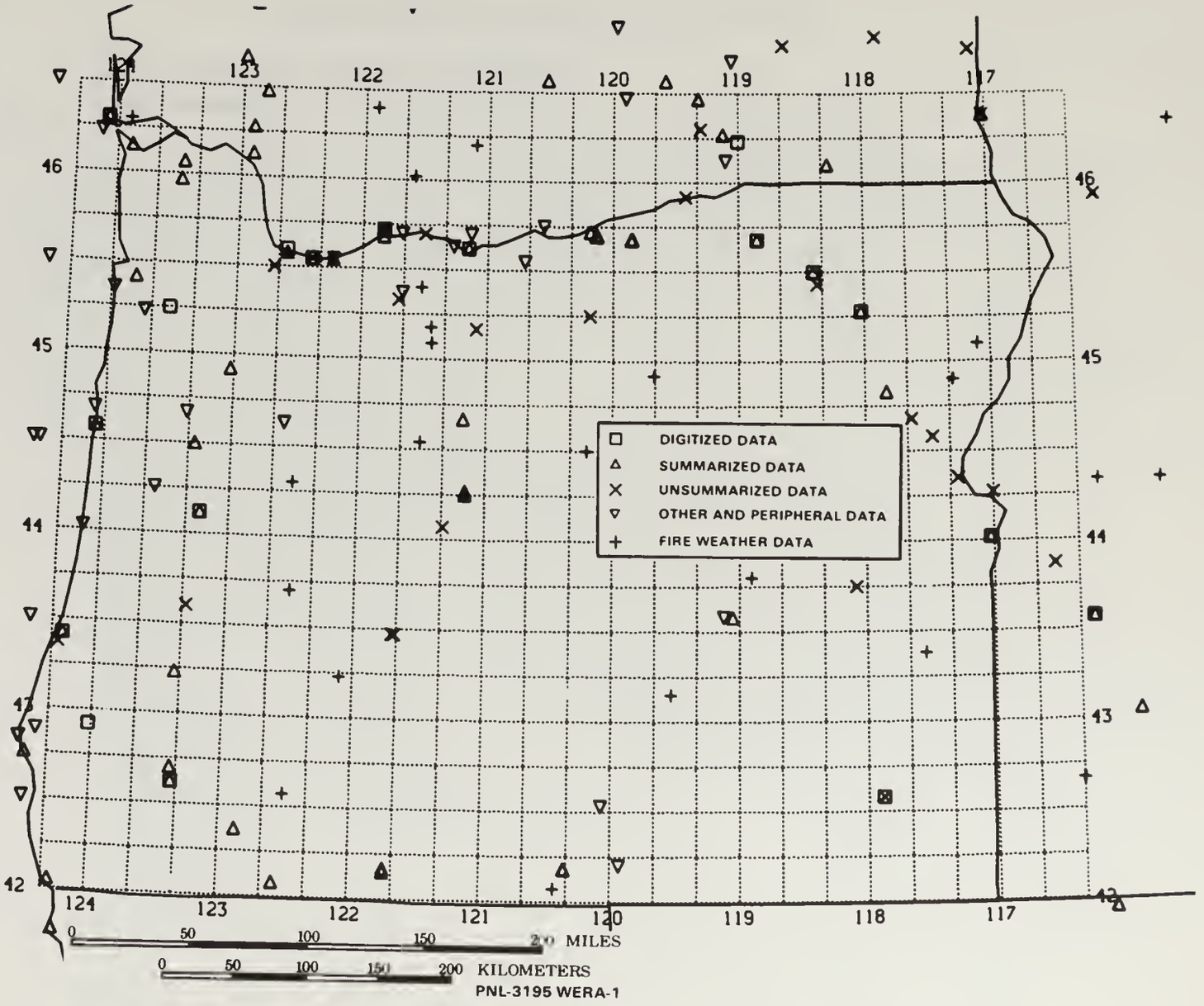


FIGURE 6.5. Location of Stations Used in Oregon Resource Assessment

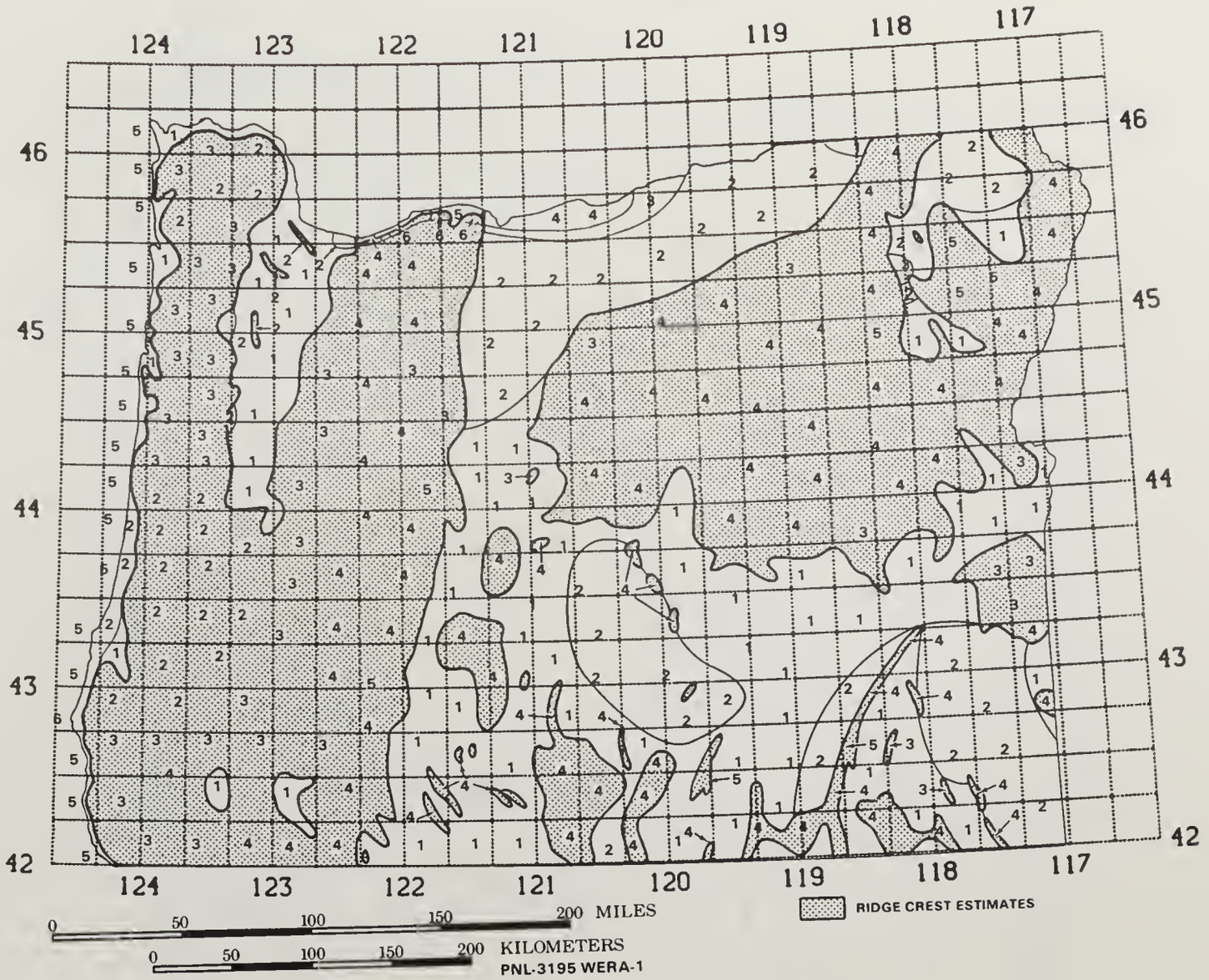


FIGURE 6.6. Oregon Annual Average Wind Power

Classes of Wind Power Density at 10 m and 50 m[a]

Wind Power Class	10 m (33 ft) Wind Power Density, watts/m²	10 m (33 ft) Speed,[b] m/s (mph)	50 m (164 ft) Wind Power Density, watts/m²	50 m (164 ft) Speed,[b] m/s (mph)
	0	0	0	0
1	100	4.4 (9.8)	200	5.6 (12.5)
2	150	5.1 (11.5)	300	6.4 (14.3)
3	200	5.6 (12.5)	400	7.0 (15.7)
4	250	6.0 (13.4)	500	7.5 (16.8)
5	300	6.4 (14.3)	600	8.0 (17.9)
6	400	7.0 (15.7)	800	8.8 (19.7)
7	1000	9.4 (21.1)	2000	11.9 (26.6)

(a) Vertical extrapolation of wind speed based on the 1/7 power law.
(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 6.1. Areal Distribution (km^2) of Wind Power Classes in Oregon

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	210,000	84.	250,000	100.
2	28,000	11.	40,000	16.
3	4,100	1.6	12,000	4.7
4	7,300	2.9	7,800	3.1
5	430	0.17	460	0.18
6	27	0.01	27	0.01
7	0	0.00	0	0.00

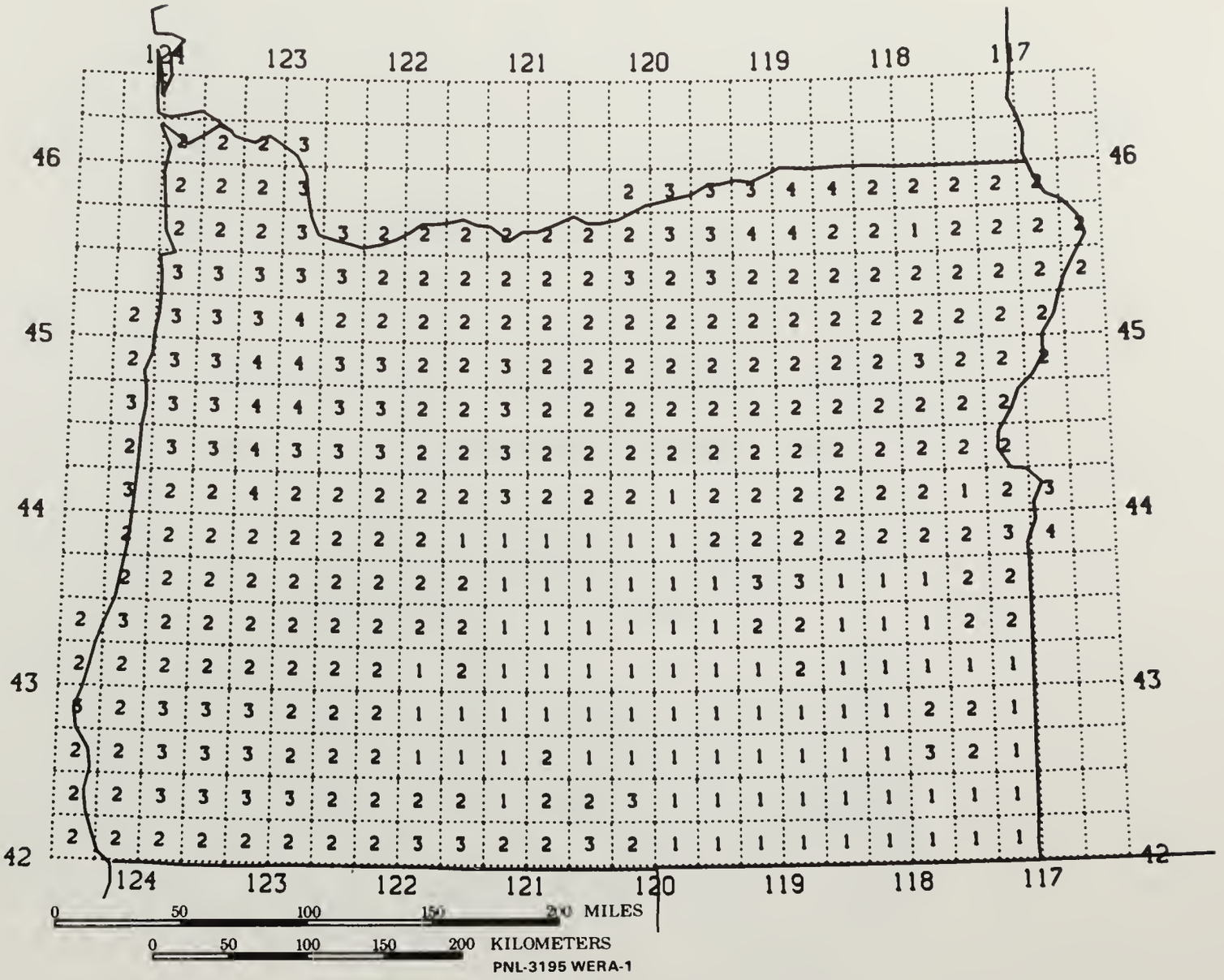
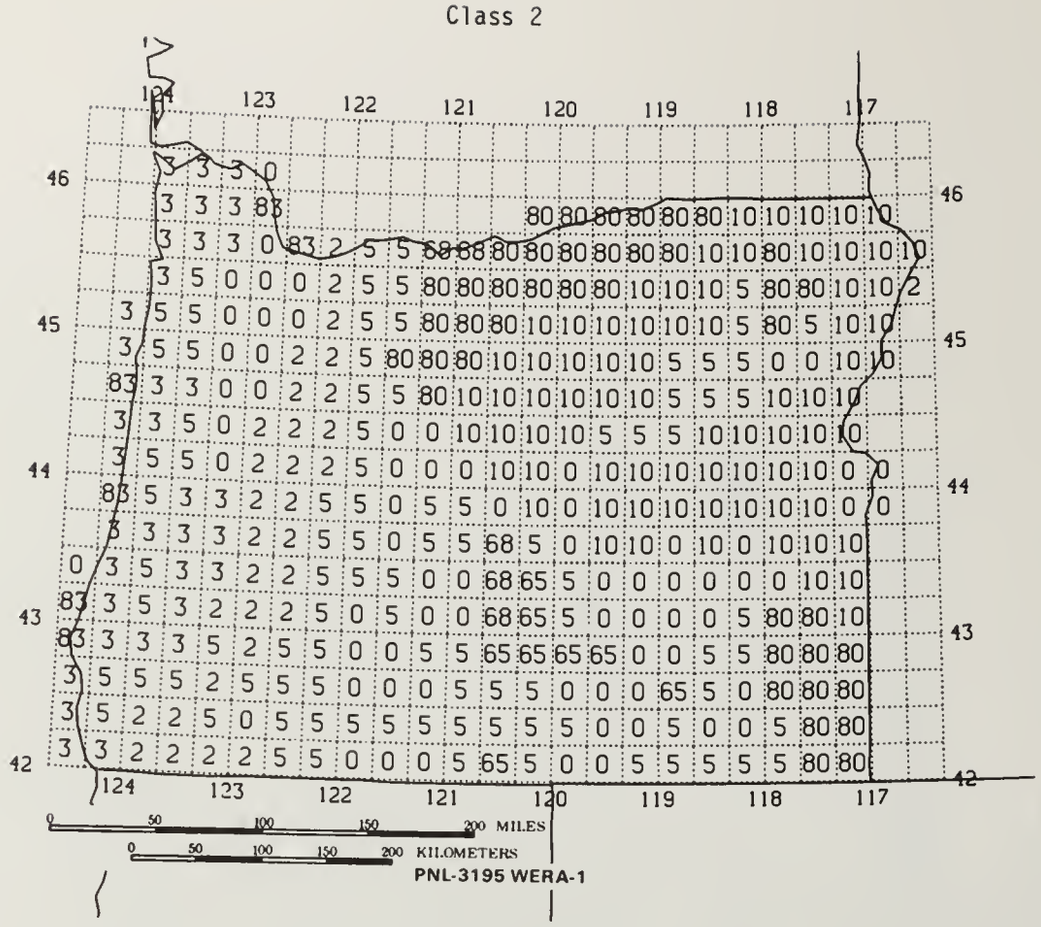


FIGURE 6.7. Certainty Rating of Oregon Wind Resource

CERTAINTY RATING LEGEND

Rating	Definition
1	The lowest degree of certainty. A combination of the following conditions exists: 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	A low-intermediate degree of certainty. One of the following conditions exists: 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	A high-intermediate degree of certainty. One of the following conditions exists: 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.



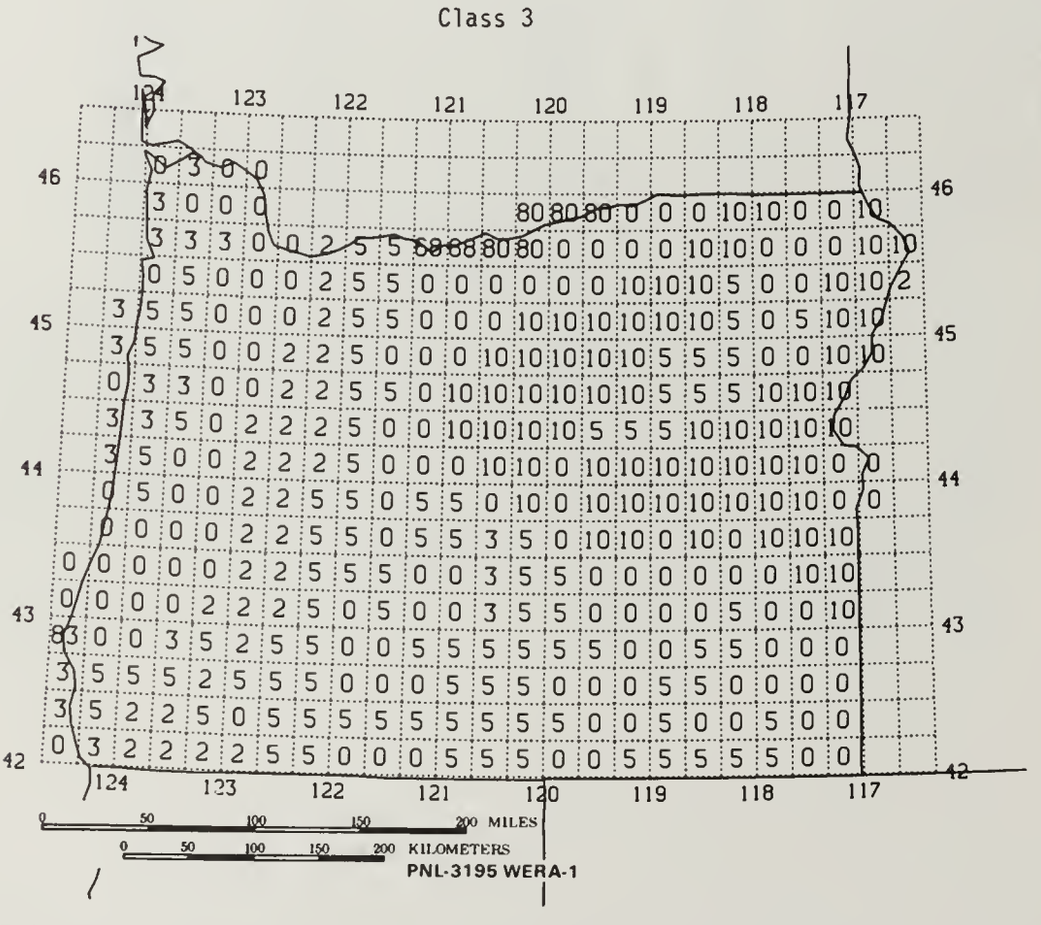
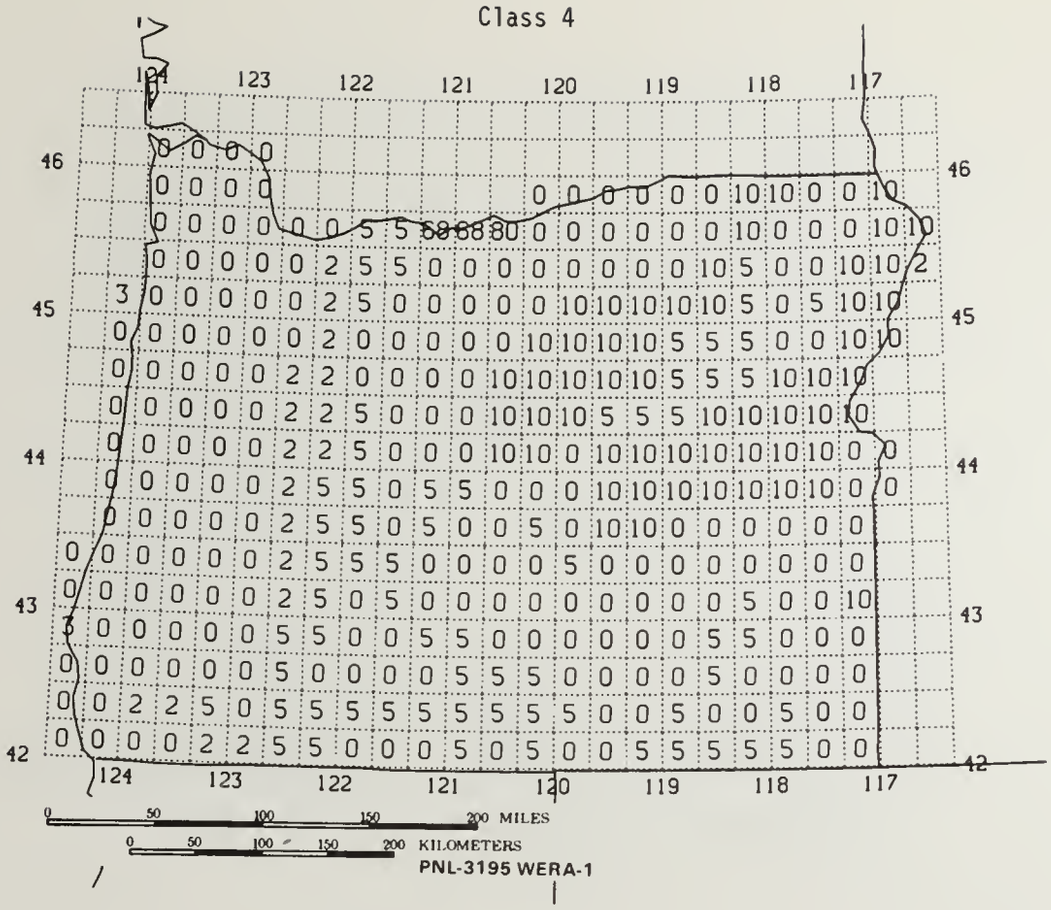


FIGURE 6.8. Areal Distribution of Wind Resource in Oregon (Power Classes 2 and 3); Percent of Land Area With or Exceeding Power Class Shown.



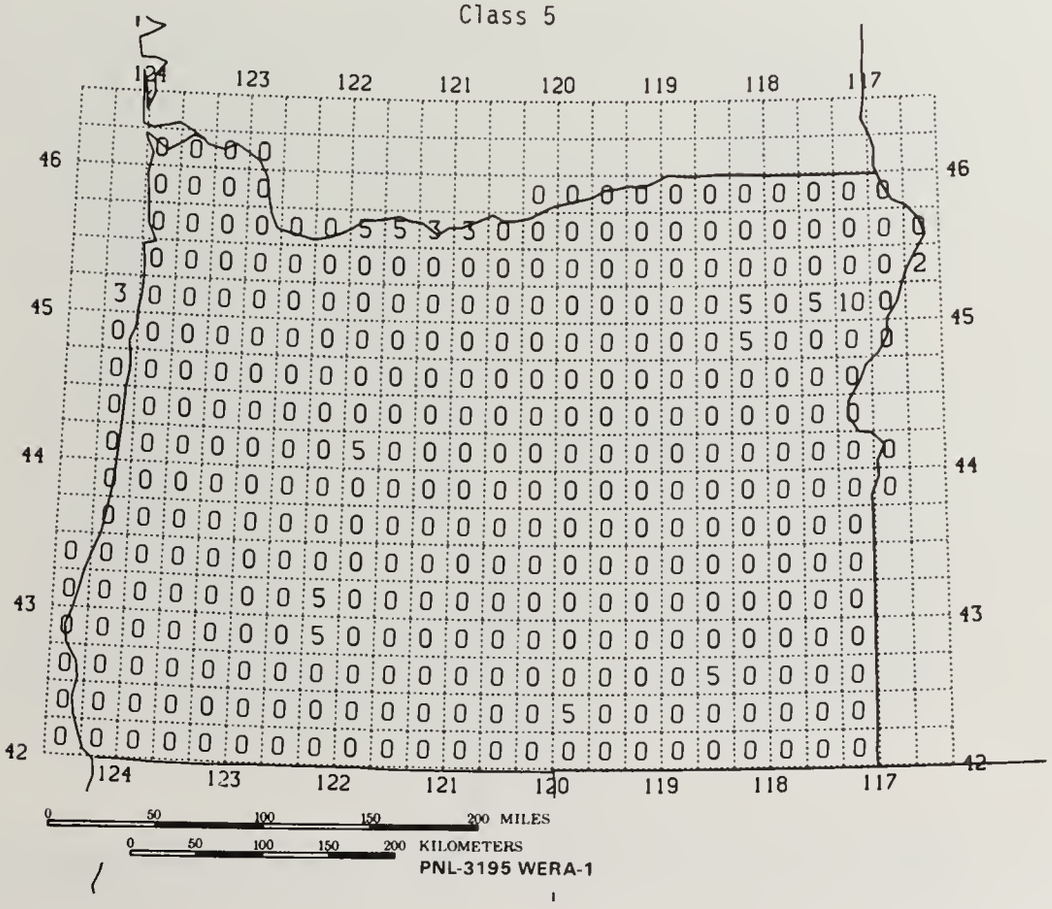
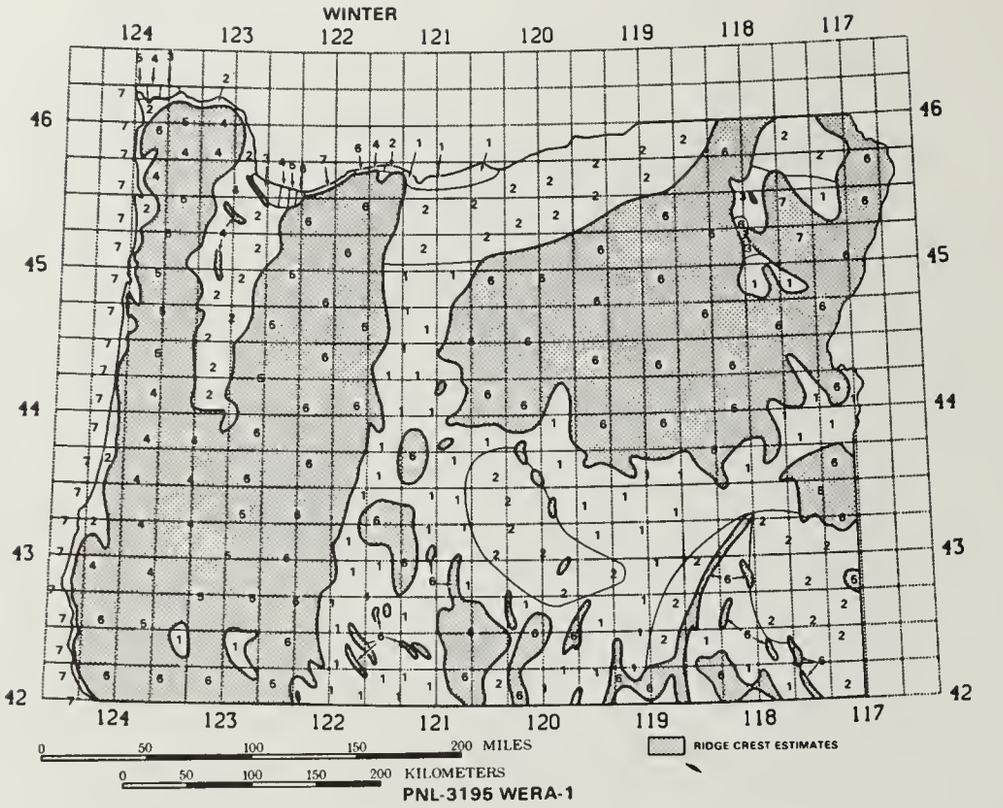


FIGURE 6.8 (Continued). Areal Distribution of Wind Resource in Oregon (Power Classes 4 and 5); Percent of Land Area With or Exceeding Power Class Shown.



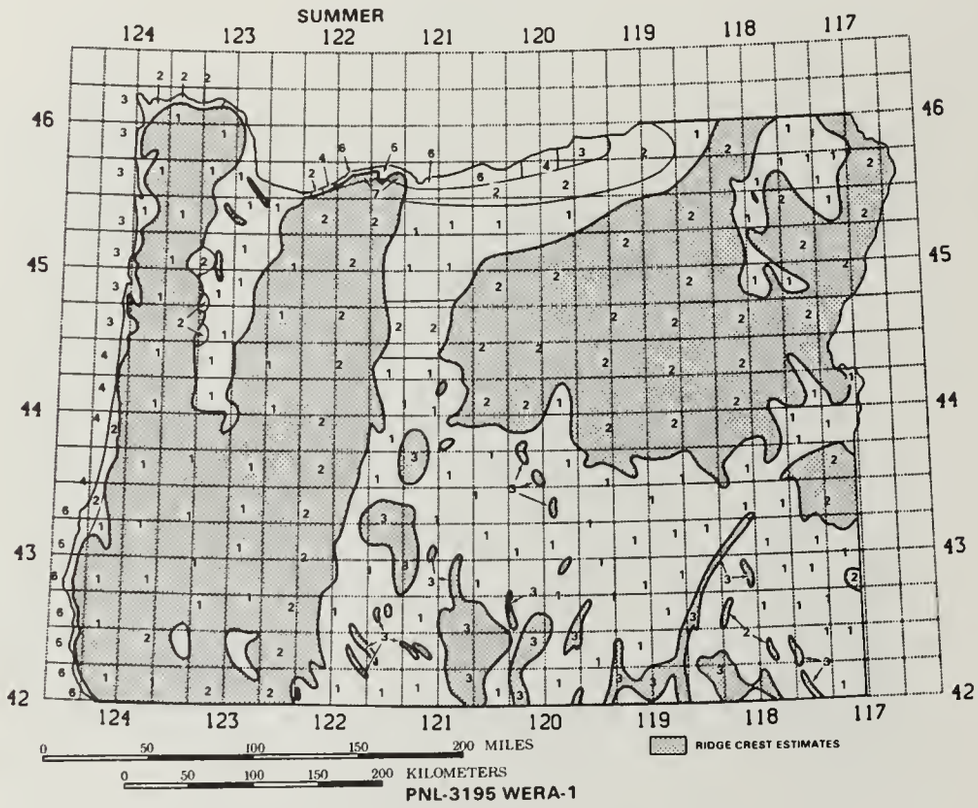
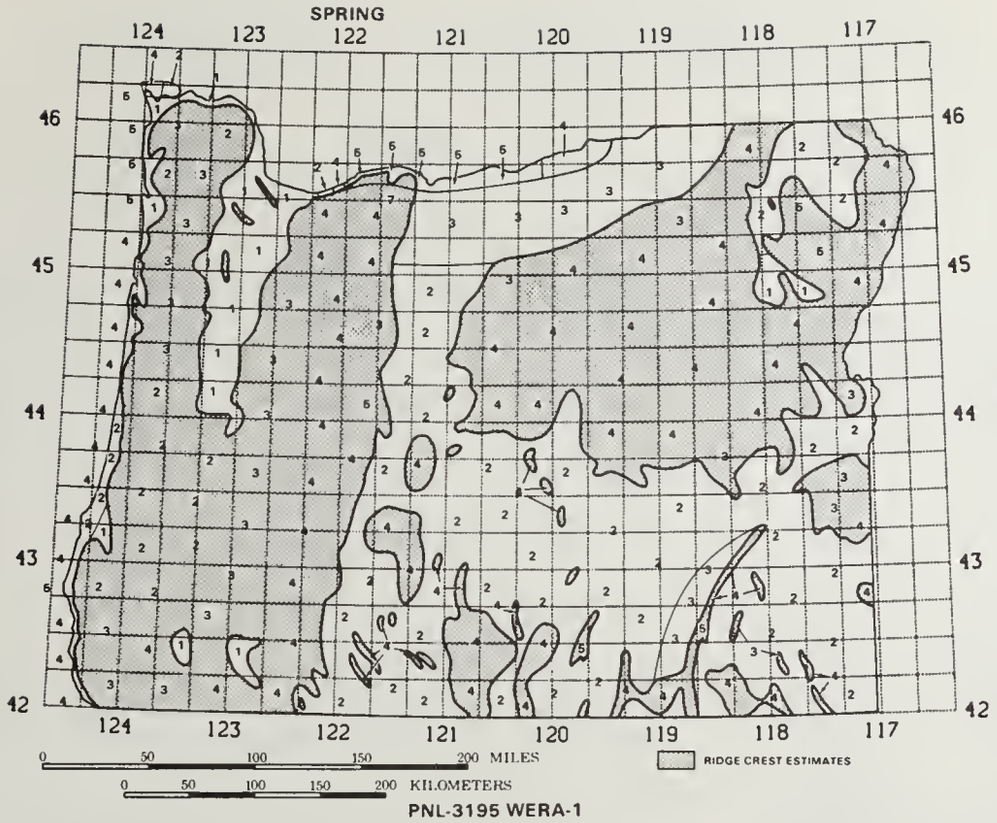


FIGURE 6.9. Seasonal Average Wind Power in Oregon (Winter, Summer)



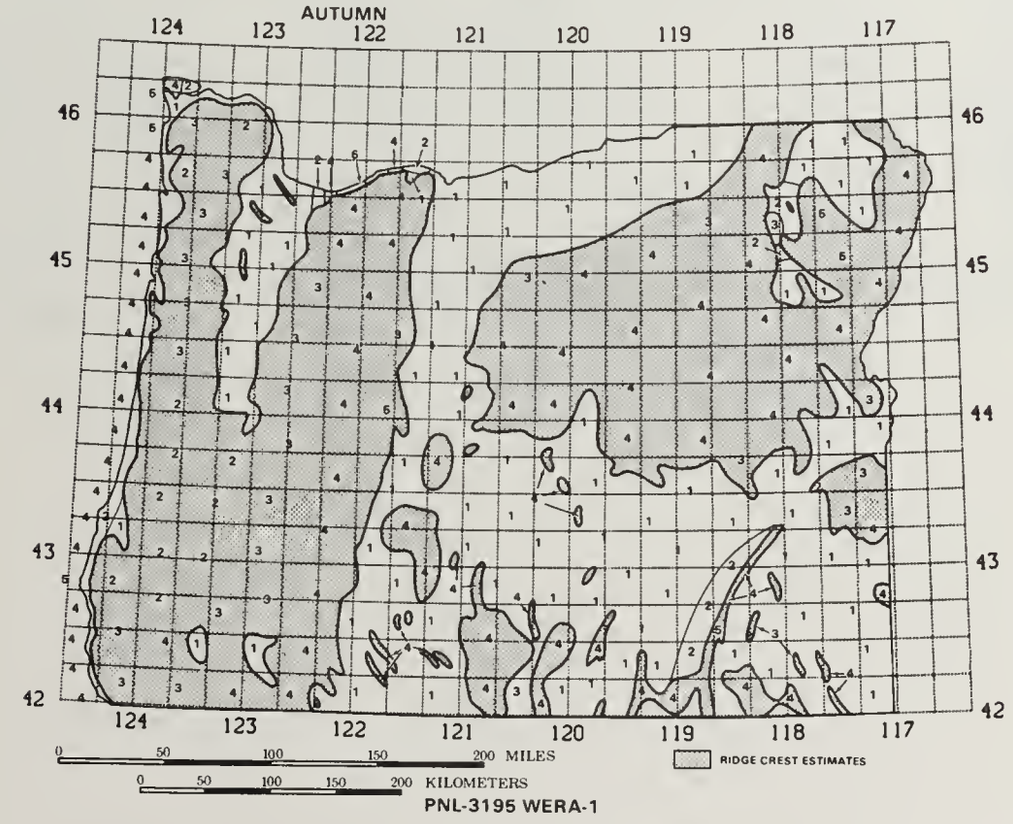


FIGURE 6.9 (Continued). Seasonal Average Wind Power in Oregon (Spring, Autumn)

TABLE 6.2. Oregon Stations with Graphs of the Wind Characteristics

Station	Station Name[a]	Latitude, Degrees North	Longitude, Degrees West	Elevation of Station, m	Period of Record, Month/Year	Anemometer Height, m	Annual Average Wind Speed, m/s			Annual Average Wind Power, watts/m²		
							At Anemometer Height, m	At 10 m	At 50 m	At Anemometer Height, m	At 10 m	At 50 m
Eugene, Oregon	Mahlon Sweet Field	44.12	123.22	111	06/62-12/76	6.1	3.6	3.8	4.8	53	66	131
La Grande, Oregon	La Grande Airport	45.28	118.02	824	12/48-12/53	10.1	4.5	4.5	5.6	151	151	300
Meacham, Oregon	Meacham Airport	45.50	118.40	1236	01/52-02/75	8.8	2.9	2.9	3.7	28	30	59
Newport, Oregon	Newport CAA	44.58	124.07	49	08/49-11/50	10.7	4.6	4.5	5.7	145	141	281
North Bend, Oregon	North Bend Airport	43.42	124.25	9	04/59-12/76	6.1	4.4	4.8	6.0	110	136	271
Ontario, Oregon	Ontario Airport	44.02	117.02	668	08/51-12/54	10.1	3.2	3.2	4.0	63	63	125
Pendleton, Oregon	Pendleton Airport	45.68	118.85	459	09/60-12/76	6.1	4.2	4.6	5.7	102	126	251
Portland, Oregon	Portland International Airport	45.60	122.60	8	08/58-12/76	6.1	3.7	3.9	5.8	72	89	177
Rome, Oregon	Rome State Airport	42.58	117.88	1234	10/49-11/50	8.8	3.7	3.8	4.7	78	82	164
Sexton SMT. Oregon	Sexton Summit WBO	42.62	123.37	1171	01/53-12/76	17.7	5.3	4.8	6.1	165	129	258
Troutdale, Oregon	Troutdale Airport	45.55	122.40	13	01/48-03/53	8.5	3.8	3.9	4.9	108	116	230

[a]CAA-Civil Aeronautics Administration Facility; WBO-Weather Bureau Office.

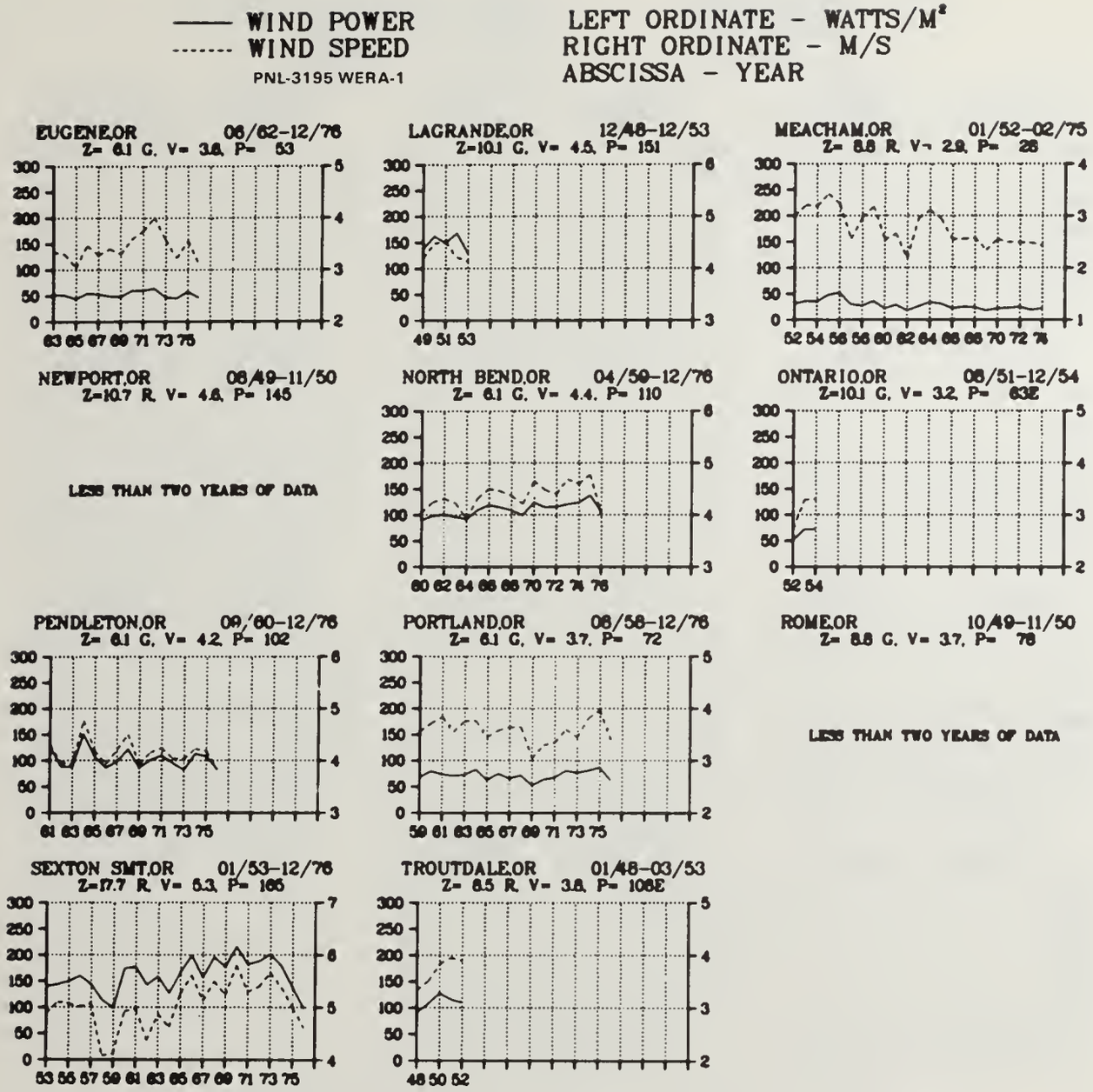


FIGURE 6.10. Interannual Wind Power and Speed for Oregon

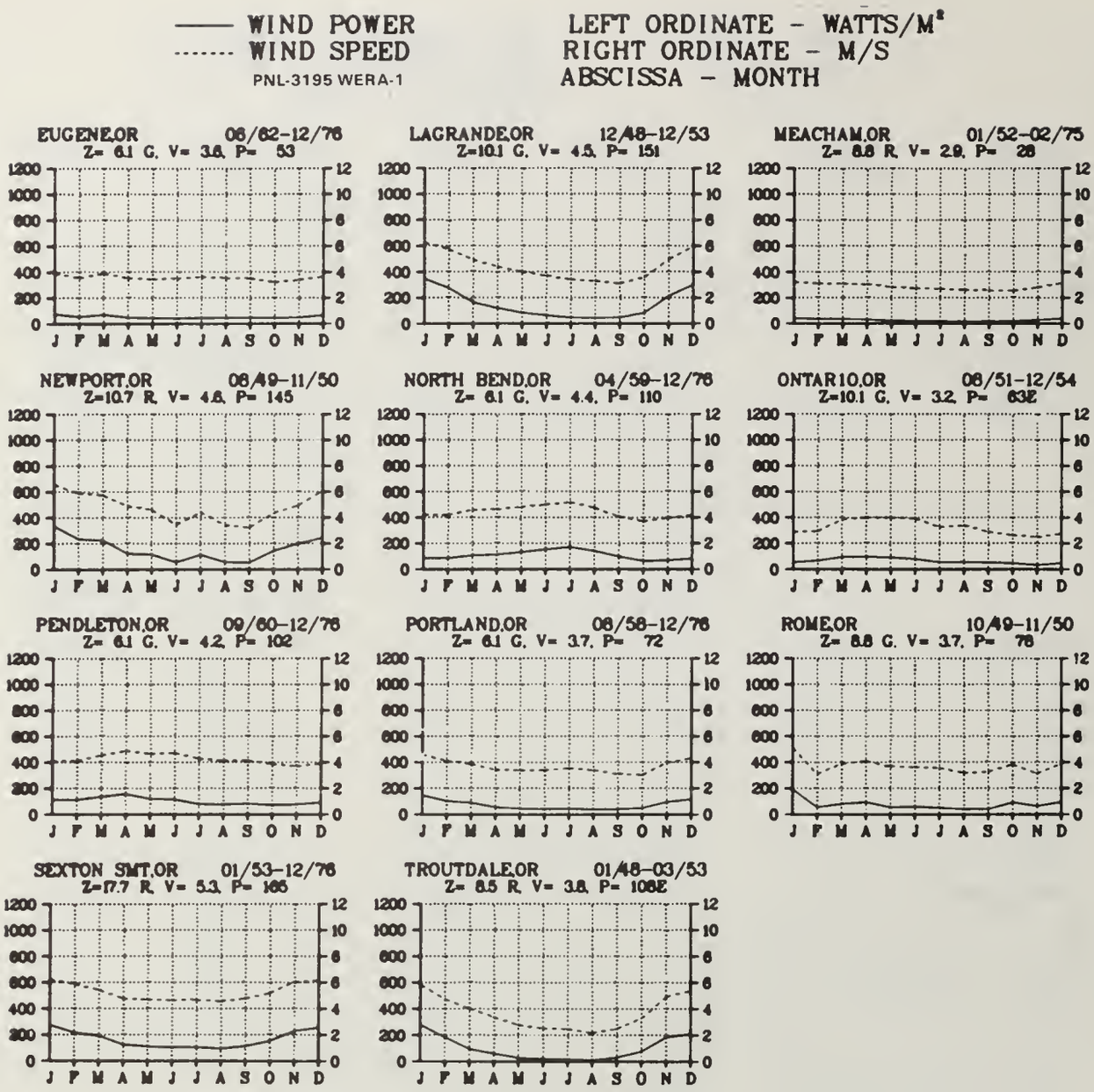


FIGURE 6.11. Monthly Average Wind Power and Speed for Oregon

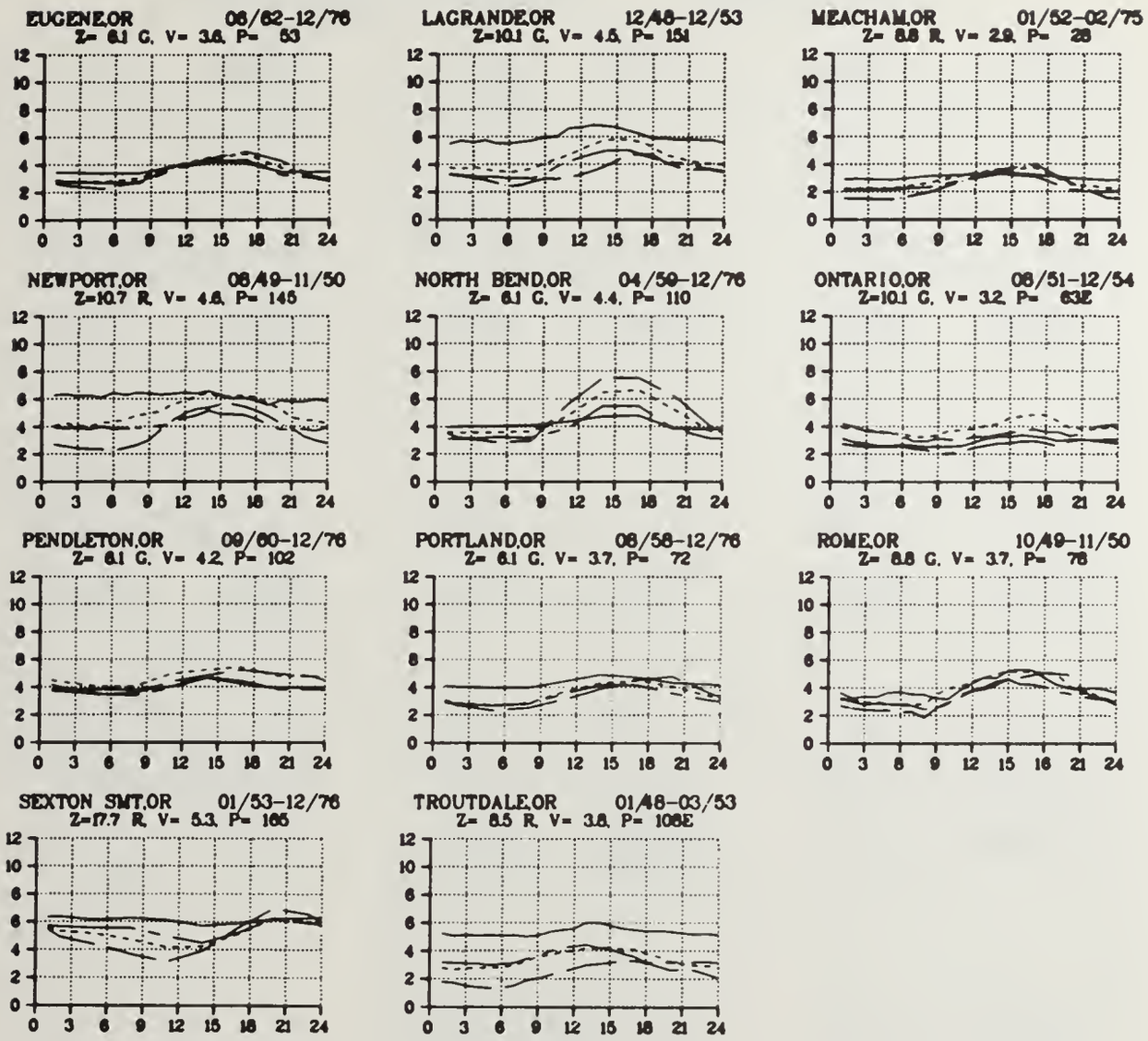


FIGURE 6.12. Diurnal Wind Speed by Season for Oregon

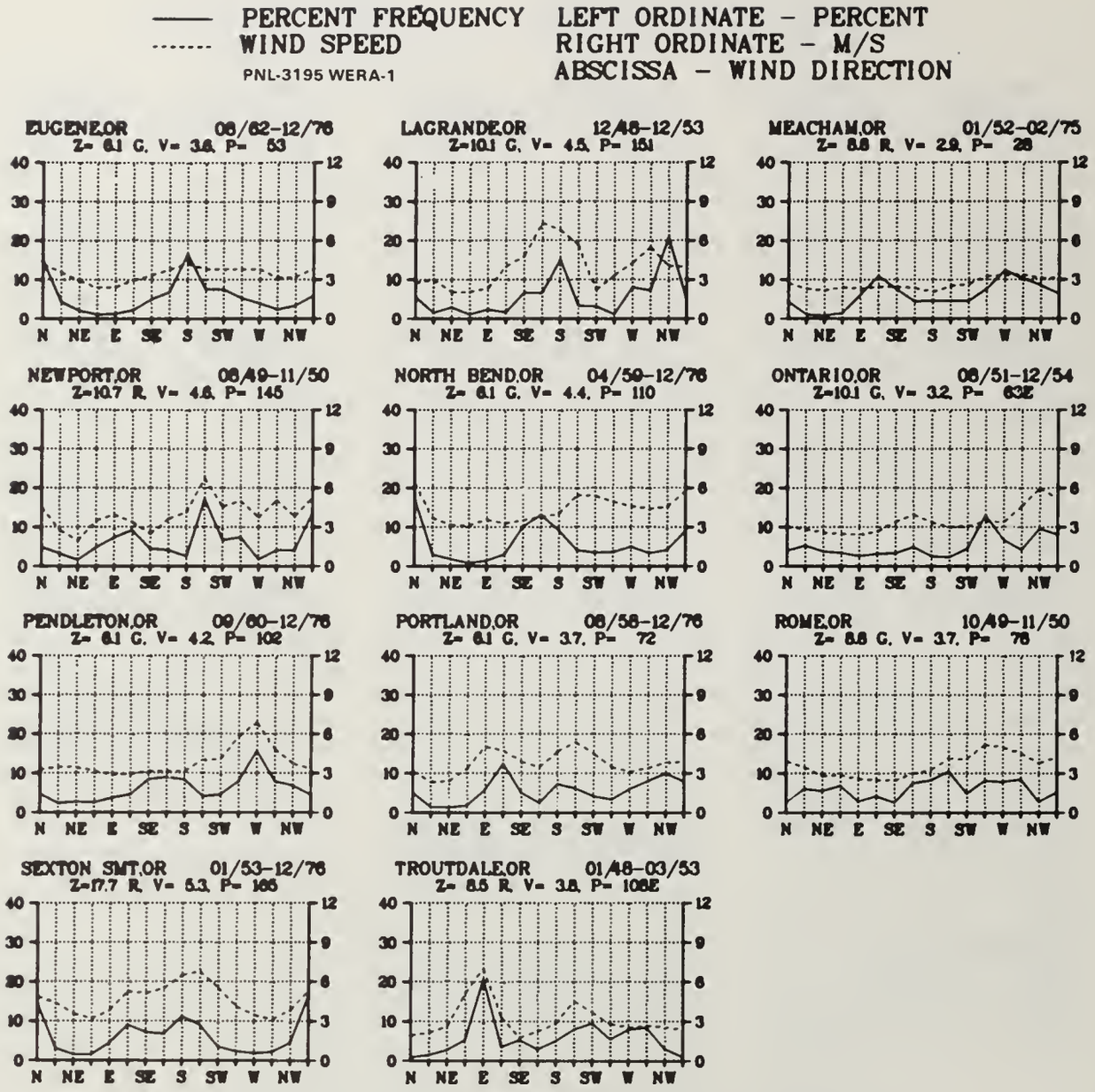


FIGURE 6.13. Directional Frequency and Average Speed for Oregon

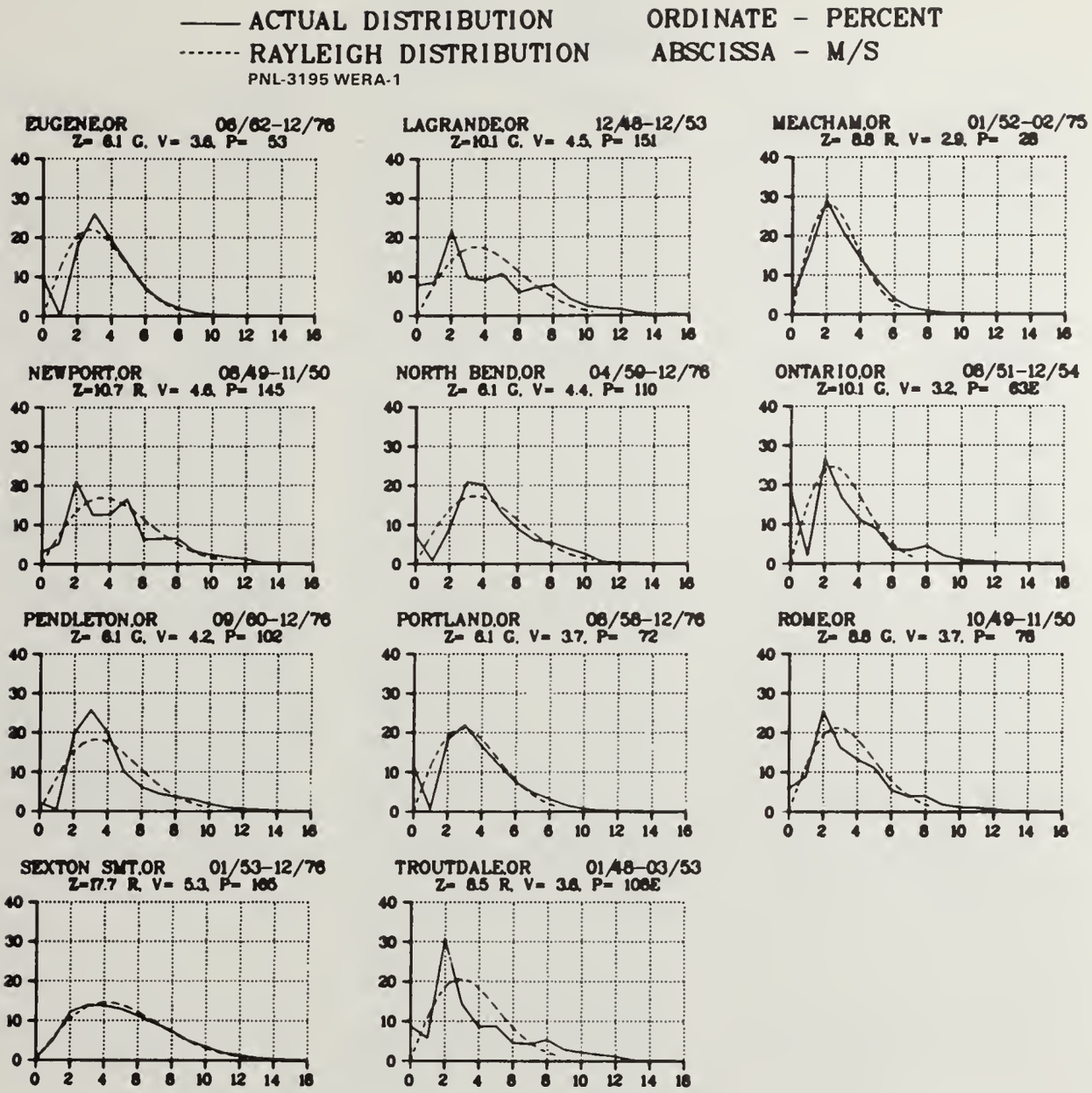


FIGURE 6.14. Annual Average Wind Speed Frequency for Oregon

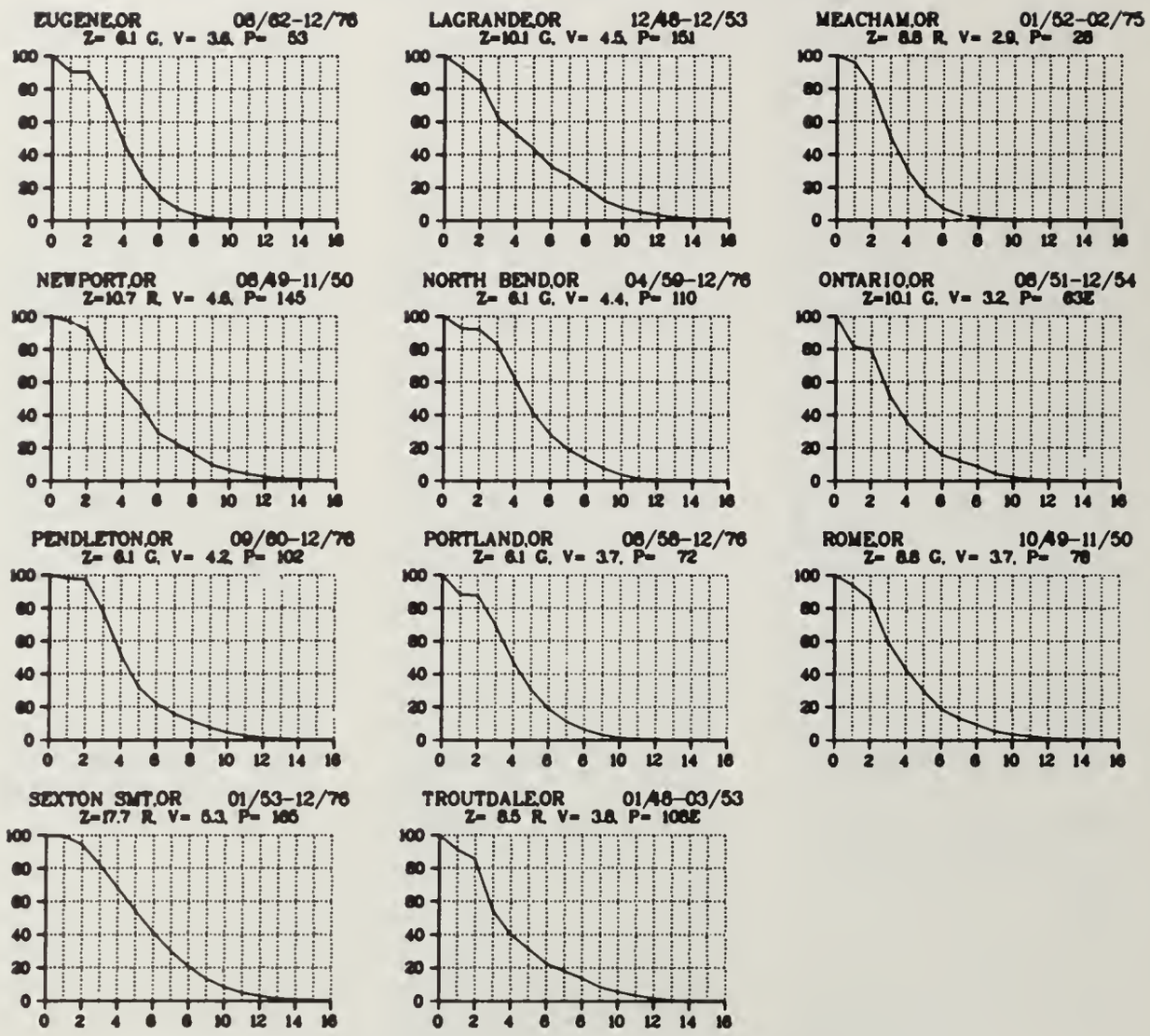


FIGURE 6.15. Annual Average Wind Speed Duration for Oregon

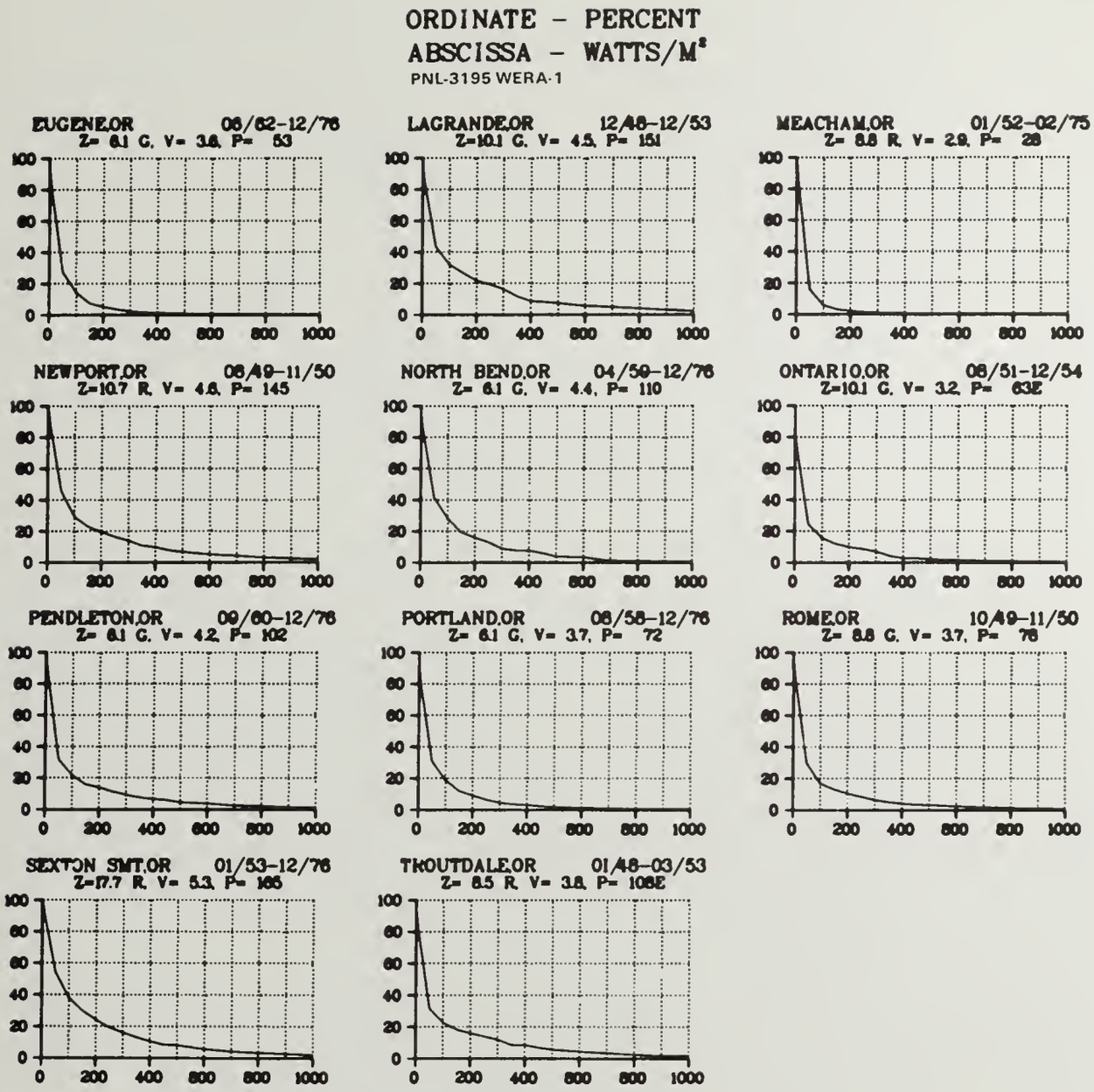


FIGURE 6.16. Annual Average Wind Power Duration for Oregon

WASHINGTON

CHAPTER 7: WASHINGTON

Washington covers an area of 176,617 km^2 (68,192 mi^2). Most of Washington's population (2,413,244 in 1970) lives in the Puget Sound region of western Washington. Over 1/2 million people live in Seattle, which is the largest city in the state and in the Northwest. Two other large cities in Washington are Spokane and Tacoma, each with populations over 150,000. Other major towns and cities are fairly well distributed throughout the nonmountainous areas of the state (Figure 7.1).

The state, located in the northwest corner of the continental United States, is divided by the Cascade Range, which extends north to south through the western third of the state (Figure 7.2). This mountain range separates the marine climate of western Washington from the arid climate of eastern Washington.

Most of the state is hilly and mountainous, with local relief exceeding 150 m (500 ft), as shown in Figure 7.3. Throughout most of the Cascade Range and Olympic Mountains, local relief exceeds 1,000 m (3,000 ft), but much of this land area is roadless and not very accessible. However, local relief is less than 150 m (500 ft) westward and southward from the Puget Sound area to Hoquiam and to Vancouver and in the Columbia Basin-Palouse Hills area of eastern Washington.

Wind data are fairly abundant in the Puget Sound area and lowlands of western Washington (Figures 7.4 and 7.5). Of stations on the Pacific coast, only two with summarized or digitized data--Tatoosh Island and North Head--appear well exposed to the prevailing strong winds. Wind data stations are scattered throughout the Columbia Basin and Palouse Hills and lowlands of eastern Washington, but many of these stations do not have summarized or digitized data. In the Cascade Range, summarized or digitized wind data from the National Climatic Center (NCC) are only found in two primary corridors--the Columbia River corridor along the Oregon border (Stevenson, The Dalles, plus some other Oregon stations) and the central Washington corridor (North Bend, Stampede Pass, Ellensburg). Fire weather data are abundant in the forested mountains of Washington, but only those stations for which more than 70% of the single daily observations during the fire season exceeded 3.5 m/s are shown in Figure 7.5.

7.1 ANNUAL AVERAGE WIND POWER

The annual average wind power map for Washington (Figure 7.6) shows class 4 or higher wind power in the Columbia River corridor along the Oregon border, the central Washington corridor (Ellensburg area), the offshore and exposed sites along the Pacific coast, and the higher exposed mountain summits and ridge crests in the Olympic Mountains, the Cascade Mountains, the mountains of northeastern Washington, and the Blue Mountains in southeastern Washington. The open ridge crests in southcentral Washington, east of the Cascades, are also estimated to have class 4 or higher wind power.

The Columbia River corridor straddles the Oregon-Washington state border from just east of Portland, Oregon, to just west of Boardman, Oregon, which is about 75 km (45 mi) west of Pendleton, Oregon. The Columbia River gorge between The Dalles and Portland provides a low-elevation passageway for intrusions of the continental air masses in the interior of the Columbia Basin east of the Cascade Mountains and the maritime air masses of the Pacific coast. In summer, strong surface pressure gradients develop across the Cascades that force the air to flow rapidly eastward from the cool, dense maritime air west of the Cascades to the hot, less dense air in the Columbia Basin. In winter, the air in the Columbia Basin is usually cold and dense in comparison to the maritime air, and the winds blow westward through the gorge. The windiest locations change with the season and are near the downwind end of the gorge. Ridge crests and summits adjacent to the gorge may have higher wind power than areas in the gorge. For example, Mt. Augspurger has higher wind power than does Cascade Locks, in Oregon, 20 km to the southwest.

The central Washington corridor, near Ellensburg, lies to the east of another breach in the Cascade Range that separates maritime and continental air masses. Unlike the Columbia River gorge, this breach consists of relatively low-elevation mountain passes and a long, wide valley extending east-southeast from the passes. In late spring and summer, the cool, marine air entering western Washington is usually deep enough to flow over the passes and accelerate eastward through the valley corridor into the Columbia Basin. During these two seasons, the wind resource in this wind corridor and ridges to the east of Ellensburg is class 6.

The class 5 power estimates along the Washington coast represent offshore and exposed coastal areas, e.g., open shorelines that are not sheltered from the prevailing winds. The winds may be accelerated around and over capes and headlands, where exposed areas can have class 6 or 7 power. The abrupt increase of surface roughness because of vegetation and topography inland from the coastline rapidly attenuates the wind resource landward of the coastline. For example, Quillayute Airport is located in a forested, hilly environment 5 km (3 mi) from the Pacific coast and has only class 1 wind power. On the other hand, Hoquiam Airport is located at the east end of Grays Harbor, about 15 km (10 mi) from the Pacific coast, and has class 4 wind power.

Shorelines in the northern Puget Sound area and San Juan Islands that are well exposed to the prevailing southeast and southwest winds are estimated to have class 3 wind power. The Strait of Juan de Fuca between the mountainous Olympic Peninsula and Vancouver Island, Canada, is a corridor over 100 km (60 mi) long where the winds are often channeled and enhanced. The west end of the Strait of Juan de Fuca is estimated to have class 3 and 4 wind power, as strong easterly winds frequently occur here during the colder months. In late spring and summer, moderate-to-strong west-northwest winds frequently occur in the central and eastern portions of the Strait of Juan de Fuca. However, the Olympic Mountains appear to shelter these areas from the strong southwest and southeast winds of the Pacific coast, so the estimated annual average power is only class 2. The Columbia River outlet is another corridor where strong easterly winds frequently occur during the colder months.

Inland areas of western Washington have class 1 power, based on the numerous data stations analyzed. Even exposed sites, such as the Seattle-Tacoma International Airport, have only class 1 wind power. Tower data at levels near 50 m (164 ft) in western Washington also indicate class 1 wind power. The very high surface roughness (e.g., forests and woodlands) throughout western Washington significantly reduces the wind speeds in the lowest 50 m above ground. Even along the Pacific coast, the abrupt increase in surface roughness rapidly attenuates the wind resource landward of the coastline. Areas in inland western Washington near long valley outlets from the Cascades, such as the North Bend area, appear to have at least class 2 wind power. Also, exposed hilltops in the class 1 areas can usually be expected to have at least class 2 wind power.

The Columbia Basin, Palouse Hills and lowlands of eastern Washington have class 1 and 2 wind power (except for the Ellensburg corridor). Small areas in or near long valley outlets from the Cascades, such as the Wenatchee River and Lake Chelan outlets, may have several power classes higher wind power than other Columbia Basin locations. Areas shielded by terrain such as the Yakima Valley (from Yakima southeast to Richland) and the western end of the Columbia Basin (Richland north to Moses Lake and west to Wenatchee), are estimated to have class 1 wind power. The class 2 estimates generally refer to hilltops in the Palouse Hills and open plains and uplands in the Columbia Basin. Some of the higher hilltops in the Palouse Hills may have class 3 power.

Prevailing strong winds are generally west to southwest in the Columbia Basin, but are influenced by nearby terrain. Long open ridges oriented perpendicular to the prevailing strong winds and with optimum slope may enhance the wind speeds considerably. For example, one site on Rattlesnake Ridge in southcentral Washington has about class 7 annual average wind power, whereas another site further west on the ridge indicates only class 4 power. The map value of class 4 represents sites where the winds are not strongly enhanced by the terrain.

7.1.1 Certainty Rating of the Wind Resource

High certainty ratings of 4 are given over much of the nonmountainous areas of western Washington and in parts of the Columbia Basin of eastern Washington (Figure 7.7). However, these areas are estimated to have a low annual average wind resource (class 1 or 2). No areas in Washington combine a large wind resource (class 4 or greater) with a high certainty. Two of the coastal areas, with long-term data at exposed sites and class 5 power, have high-intermediate certainty ratings. All other coastal areas have a low-intermediate certainty rating, as offshore marine data and limited coastal data were used in estimating the coastal wind resource.

The Columbia River corridor along the Oregon border between Arlington, Oregon, and Stevenson, Washington, has considerable data and is estimated to have class 4 or higher power, but a low-intermediate certainty rating was given to these areas because of the extreme geographic variability of the wind resource. The Ellensburg valley is another area that has a large wind resource (class 4 power) but a low-intermediate certainty, because of the large geographic variability expected.

Most of the Columbia Basin has a high-intermediate to high certainty rating, except for the Palouse Hills which have low-intermediate certainty.

The mountainous regions have a low-intermediate certainty rating, except for a few areas with high-intermediate certainty where both winter and summer data at exposed ridge crest or mountain summit sites are available.

7.1.2 Areal Distribution

The Cascade Range and Olympic Mountains occupy about 27% of the state and contribute about 1.1% of the land area of the state to class 4 and higher wind power. These same areas also contribute about 26% to the 78% of the state that is rated as class 1 in Table 7.1. Figure 7.8 shows that a small percentage (2 to 5%) of cell area is contributed to power class 5 and greater by the Cascade Range, Olympic Mountains, and the mountains of northeastern Washington. High per-cell area contributions to class 4 power are associated with the Ellensburg and Columbia River wind corridors. The plains areas of the Columbia Basin contribute mainly to power class 2.

7.2 SEASONAL WIND VARIATIONS

Wind power maps for each season are shown on facing pages in Figure 7.9. Winter is the season of maximum wind power along the coastal areas, most inland areas in western Washington except the central to eastern portions of the Strait of Juan de Fuca, and over mountain summits and ridge crests throughout the state. In the Columbia Basin and Palouse Hills, spring is the season of maximum wind power. A summer wind power maximum is found at the eastern end of the Columbia River corridor, the Ellensburg corridor in central Washington, and the central to eastern portions of the Strait of Juan de Fuca. Except for these wind corridors, summer is generally the season of minimum wind power throughout the state.

7.2.1 Winter

In the winter, class 6 and 7 wind power is estimated for exposed coastal and offshore areas, the western part of the Columbia River gorge, and exposed ridge crests and summits (except for the lower forested ridges and summits in western Washington). On the western slopes of the Cascades, strong down-valley winds occasionally occur in and near the outlets of long valleys, such as the Skagit, Skykomish, and Snoqualmie River valleys. Limited data indicate that such areas may have class 4 or better wind power in the winter season. These strong easterly corridor winds on the west side of the Cascades and the west end of the Columbia River gorge are usually associated with a relatively cold air mass (high pressure) over eastern Washington and exceptionally strong surface pressure gradients across the Cascades. The winds usually diminish significantly west of the gorge as they spread over the Vancouver-Portland lowlands.

Over northern Puget Sound the prevailing strong wind direction in winter is from the southeast, as indicated by data from Port Townsend and Whidbey Island. Locations at the downwind ends of long northwest- to southeast-oriented open fetches of water (e.g., Port Townsend) are estimated to have at least class 4 winter wind power.

7.2.2 Spring

In the spring, the estimated wind power is class 5 or higher along the Pacific coast, in the central Washington and Columbia River corridors, and on the higher exposed ridge crests and mountain summits of the Olympics and Cascades. The Palouse Hills and the southeastern portion of the Columbia Basin indicate class 3 power. The west-to-southwest orientation of the plain extending from the Columbia River corridor near The Dalles, Oregon to the Palouse Hills of southeastern Washington provides nearly unobstructed flow to the prevailing strong west-to-southwest winds. Throughout the inland areas of western Washington winds are in the class 1 power range.

7.2.3 Summer

In summer, class 5 wind power is estimated in the central and eastern parts of the Columbia River corridor (from near Stevenson, Washington to near Arlington, Oregon) and the central Washington corridor. Relatively cool, dense maritime air is funneled eastward through these corridors to the generally warmer, less dense air east of the Cascades. Exposed ridge crests and summits in and adjacent to these corridors may have higher summer wind power than in the valleys, although some of this increase may be due to terrain-induced enhancement. Based on limited pibal data available from Ellensburg, wind speeds in the central Washington corridor increase with height to about 1,000 m (3,500 ft) above sea level (MSL) and then decrease.

Small areas with class 4 or higher summer wind power may exist in and near the outlets of long valley drainages along the east side of the Cascades, such as the Wenatchee River and Lake Chelan valleys. In western Washington, the areas with highest summer wind power are the central

to eastern portions of the Strait of Juan de Fuca, as westerly winds are funneled through the strait. The Port Angeles station indicates higher wind power (class 3) in the summer than in any other season. Some offshore or better exposed shore locations in that area may have even greater power than the Port Angeles station. Wind power in summer is generally class 1 or 2 throughout the rest of Washington, including the Pacific coast and ridge crests. Coastal wind power increases from north to south in the summer.

7.2.4 Autumn

In autumn, the wind power is estimated to be class 6 in the western part of the Columbia River gorge, and class 5 along the Pacific coast and high ridge crests and mountain summits in the Cascade and Olympic Mountains. In these areas, monthly average power increases from September through November. Except for the mountainous areas, wind power is class 1 or 2 in autumn throughout most of eastern and western Washington.

7.3 FEATURES OF SELECTED STATIONS

Table 7.2 gives the location and annual wind speed and power density of thirteen stations in Washington. Graphs of other features of the wind resource are shown in Figures 7.10 to 7.16. Four of these stations are along or near the Pacific coast, two are in the Puget Sound area, two are in the Columbia River corridor, two are in the central Washington corridor, and three are in the Columbia Basin.

Dallesport is located across the river from The Dalles, Oregon, in the Columbia River wind corridor; however, the station is partially sheltered from the strong westerly winds by a 500 to 700 m (1,700 to 2,300 ft) high ridge 8 to 10 km (5 to 6 mi) west and west-northwest of the station.

Ellensburg Airport is in the central Washington wind corridor and appears to have good exposure to the strong west-northwest to northwest winds.

Hoquiam Airport is situated on a narrow peninsula near the east end of Grays Harbor and has excellent exposure to westerly winds blowing almost unobstructed across Grays Harbor from the ocean.

North Head is located on the Pacific coast near the Columbia River outlet. The wind measurements are taken on an exposed head 67 m (220 ft) MSL. This site is probably windier (by one or two power classes) than beach areas. Although only 11 months' digitized data are available, North Head was included because of its unique setting on a coastal head. Nine years' summarized data (1934 to 1942) indicate the same wind power class as this short period.

Pasco, in the southern part of the Columbia Basin of eastern Washington, has only 1 year's digitized data. A longer period of summarized data from the Pasco Airport (1961 to 1965), but with fewer than 24 hourly observations per day, indicates at least one class higher wind power than this 1-year period at Pasco Naval Air Station.

Quillayute, on the Olympic Peninsula, is about 5 km (3 mi) inland from the Pacific coast in forested, hilly terrain. Its class 1 wind power shows the effect of terrain and surface roughness on diminishing the power in the coastal area.

Seattle-Tacoma Airport is representative of an exposed upland site in the Puget Sound area.

In the Spokane area, two nearby stations--Spokane Airport and Fairchild Air Force Base--are shown. The significantly higher 10 m wind power at the Spokane Airport implies that the winds at Fairchild Air Force Base may be obstructed (e.g., by local buildings, vegetation, terrain, etc.).

Stampede Pass, located in the western end of the central Washington corridor about 80 km (50 mi) east-southeast of Seattle, is a relatively low pass (1,209 m or 3,958 ft) on the main divide of the Cascade Range. The winds through the pass are predominantly westerly and easterly.

Stevenson is located in a windy area in the Columbia River gorge about 60 km (40 mi) east of Vancouver.

Tatoosh Island is a small island off Cape Flattery, on the northwest tip of Washington. The site appears well exposed to both prevailing westerly and southerly ocean winds and easterly winds blowing out of the Strait of Juan de Fuca.

Whidbey Island Naval Air Station is on the northwest side of a large island in northern Puget Sound.

7.3.1 Interannual Wind Power and Speed

Six stations have selected periods of record of 10 years or more during which the anemometer was not moved (Figure 7.10). At five of these--Dallesport, Seattle-Tacoma and Spokane International Airports, Fairchild Air Force Base, and Stampede Pass--the

highest annual power was double or more the lowest annual power. However, the high and low wind power years may not coincide with those at a nearby site. For example, the relatively low power in 1965 to 1966 at Spokane International Airport is not evident at Fairchild Air Force Base. However, both stations show a relative maximum in 1964. The steadily increasing annual power at Stevenson from 1948 to 1951 should be viewed with caution.

7.3.2 Monthly Average Wind Power and Speed

All Pacific coast and Puget Sound area stations indicate maximum wind power in the winter (Figure 7.11). Tatoosh Island and North Head have the largest seasonal/monthly variations, with about a factor of 8 ratio between the months of highest and lowest power. Ellensburg and Dallesport indicate late spring and summer maxima. Both stations are located in wind corridors where strong westerly winds are channeled when there is relatively cool marine air west of the mountains and warmer dry air east of the mountains. The reversed seasonal trends at Stevenson and Dallesport, 50 km (30 mi) to the east, illustrate the seasonal difference in wind energy between the eastern and western parts of the Columbia River corridor. The eastern part (east of the Cascade crest) has a summer maximum and the western part a winter maximum, whereas the central part of the corridor, such as Stevenson, has high mean wind speeds throughout the year.

At Stampede Pass (a relatively low pass in the main divide of the Cascade Range), seasonal variations of the wind may not be typical of exposed ridge crests. Average summer wind power at Stampede Pass may be greater than that on nearby ridge crests, because maritime air is channeled and accelerated through this low-elevation pass eastward into the Ellensburg valley, whereas average winter power may be considerably lower than that on nearby ridge crests. For example, the wintertime average wind speed on Crystal Mountain (2,094 m, 6,900 ft), located about 35 km south of Stampede Pass, is 8.2 m/s, compared to 5.5 m/s at Stampede Pass.

7.3.3 Diurnal Wind Speed by Season

Diurnal trends vary throughout the state. Maximum diurnal variations usually occur during the spring and summer months (Figure 7.12). In winter, diurnal variations are small (<2 m/s) at all 13 stations shown, except for Stevenson in the Columbia gorge. Seattle-Tacoma Airport, Spokane, Stampede Pass, and Tatoosh Island have small diurnal variations in every season. Tatoosh Island is in an oceanic environment and has little continental influence, as prevailing winds come from the Pacific Ocean and the Strait of Juan de Fuca. Seattle-Tacoma Airport indicates smaller diurnal variations than coastal stations in western Washington where the diurnal variations are influenced by the sea breeze, especially in summer and spring. Diurnal variations are expected to be small throughout inland areas of western Washington because of the cool marine climate and relatively small diurnal temperature variations. At Spokane International Airport, diurnal variations in spring and summer are smaller than expected. Perhaps this is because of the frequent moderate northeast drainage winds at night and relatively good exposure of the station.

Dallesport, Ellensburg, Hoquiam, and Stevenson have diurnal variations exceeding 3 m/s. At Hoquiam, the maximum wind speed around 1400 to 1600 LST appears to be associated with a sea breeze flow that is strongest in the summer. Whidbey Island and Quillayute also indicate diurnal variations in spring and summer that appear to be associated with an afternoon sea breeze. At Dallesport, Ellensburg, and Stevenson, the strong afternoon and evening winds may be associated with the surge of marine air flowing from west to east through these mountain wind corridors. As the thermal and pressure gradients between the cool, marine air mass west of the Cascades and the warm, dry, air mass east of the Cascades intensify, the wind speeds usually increase. Maximum summer wind speeds occur around 1400 to 1600 LST at Stevenson and 1700 to 1800 LST at Dallesport, about 60 km (40 mi) further east. At Ellensburg, maximum summer wind speeds occur around 1800 to 1900 LST.

Limited data for exposed mountain summits and ridge crests in Washington indicate that the maximum wind speeds may occur in the late evening or night and that diurnal variations are larger in summer than winter.

7.3.4 Directional Frequency and Average Speed

Throughout most of Washington, the prevailing surface wind direction(s) are strongly influenced by the terrain (Figure 7.13). In the Columbia Basin and Palouse Hills, the strongest winds are usually from the southwest (e.g., Pasco and Spokane). Even at stations (e.g., Hanford, Moses Lake, Walla Walla) where the prevailing winds are not southwest (due to local drainage flow or terrain influences), the strongest annual average winds are usually southwest.

Strongest winds are generally southwest to south in southern Puget Sound and southeast in northern Puget Sound. (Note the high mean wind speeds from the southeast at Whidbey Island Naval Air Station. Sites with long fetches of water to the southeast may have higher mean wind speeds from that direction than at the Whidbey Island station.)

At Stampede Pass and Stevenson, the two sharp peaks in the frequency and average speed indicate that the flow is channeled by nearby terrain. Channeling also occurs at Ellensburg and Dallesport, but the prevailing strong winds are from the west-northwest to northwest.

At Tatoosh Island, highest average wind speeds are from the east, out of the Strait of Juan de Fuca. This indicates that the west end of the strait should have considerable wind power. However, because the Strait is somewhat sheltered from southerly winds, it probably has a lower mean power than Tatoosh Island.

7.3.5 Annual Average Wind Speed Frequency

The skewed frequency distributions at Ellensburg and Dallesport are caused by the large seasonal and diurnal variations in the wind speeds (Figure 7.14). Monthly and seasonal frequency distributions at stations with large seasonal variations, are usually not as skewed as the annual distribution. At sites where the wind speed distributions are highly skewed, such as Ellensburg, the annual average wind speed is not a reliable indicator of the wind power. For example, although the average wind speed is only 4.5 m/s at Ellensburg compared to 5.3 m/s at Stampede Pass, the wind power at Ellensburg is 215 watts/m^2 compared to 148 watts/m^2 at Stampede Pass.

Observer biases are evident from the peaks at 2, 5, and 8 m/s (5, 10, and 15 knots) in the distributions for Dallesport, Ellensburg, North Head, Stevenson, and Tatoosh Island.

7.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 7.15 and 7.16. Abrupt changes in the slope of the duration curves correspond to peaks in the speed frequency distribution caused by observed bias and instrument threshold velocity.

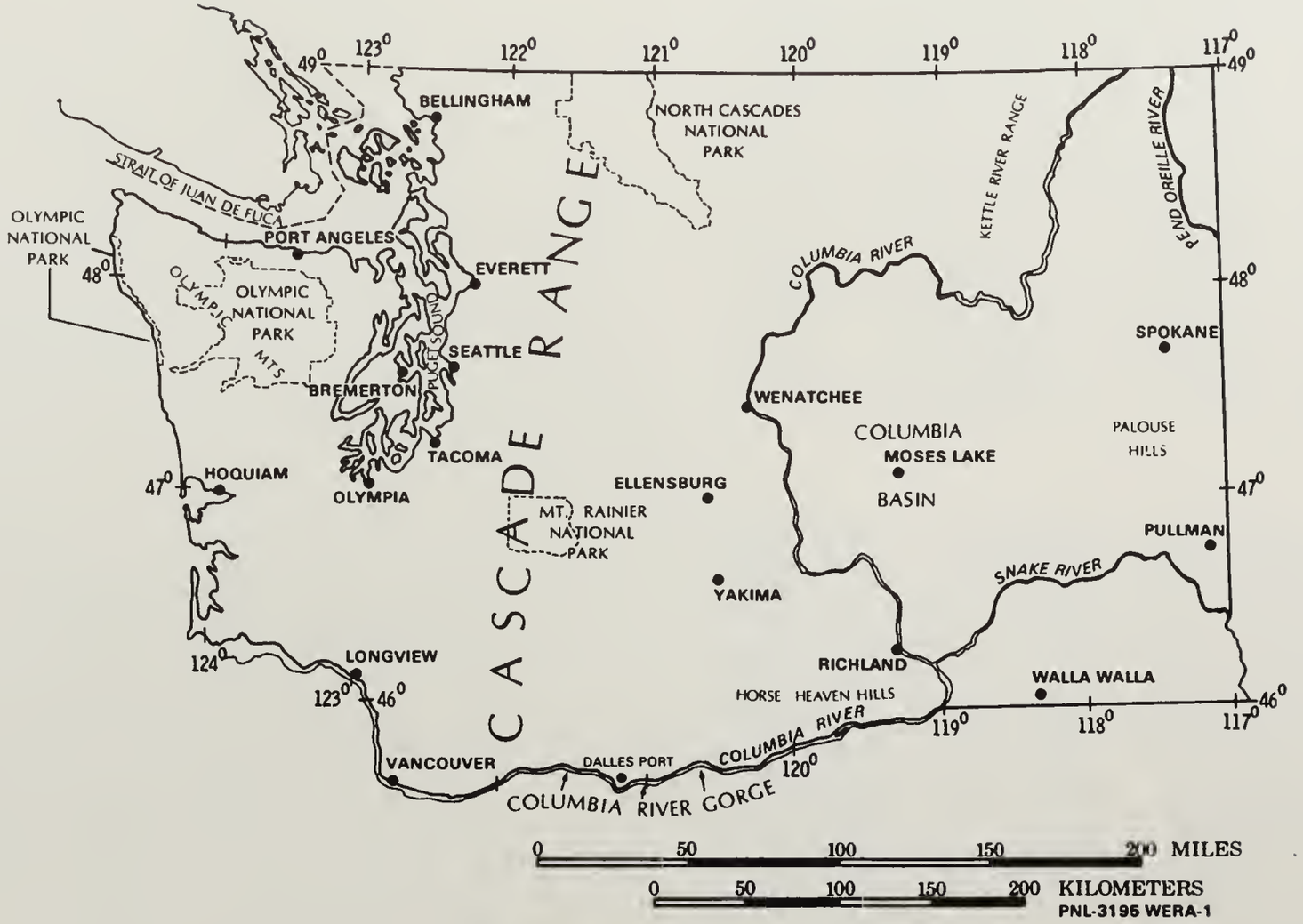


FIGURE 7.1. Geographic Map of Washington

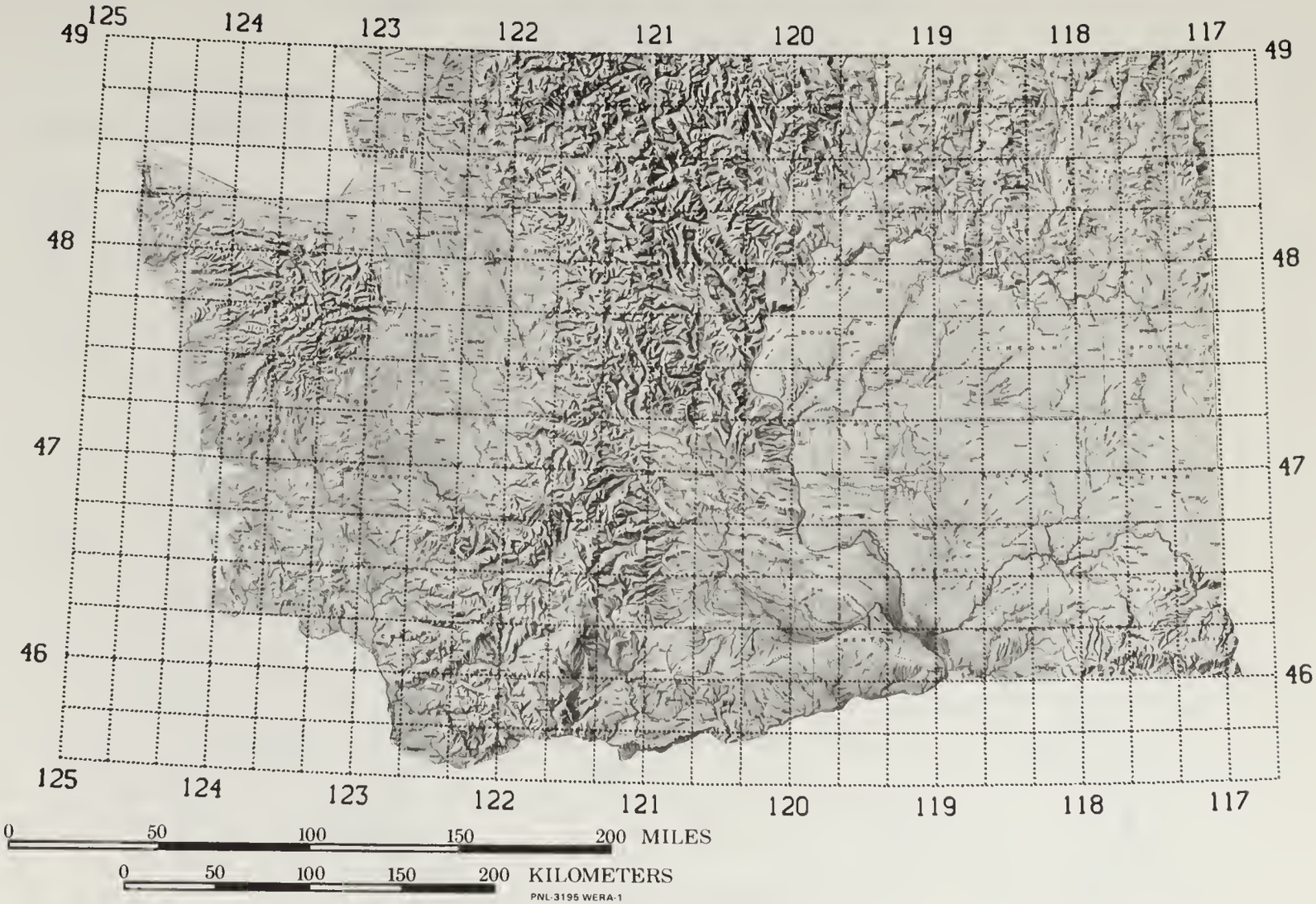


FIGURE 7.2. Topographic Map of Washington

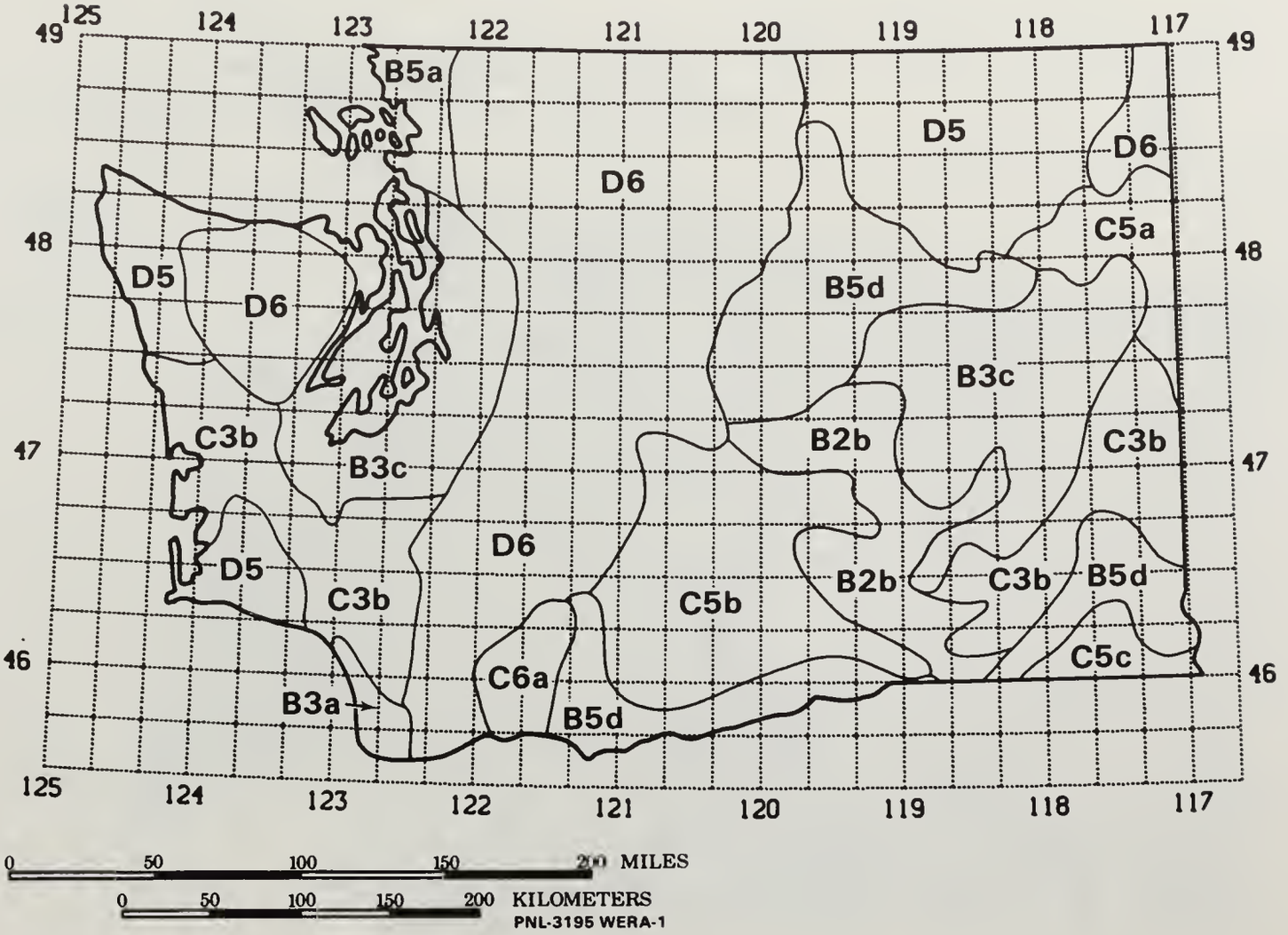


FIGURE 7.3. Land-Surface Form Map for Washington

LAND-SURFACE FORM LEGEND

PLAINS

A1	FLAT PLAINS
A2	SMOOTH PLAINS
B1	IRREGULAR PLAINS, SLIGHT RELIEF
B2	IRREGULAR PLAINS

PLAINS WITH HILLS OR MOUNTAINS

A,B3a,b	PLAINS WITH HILLS
B4,a,b	PLAINS WITH HIGH HILLS
B5a,b	PLAINS WITH LOW MOUNTAINS
B6a,b	PLAINS WITH HIGH MOUNTAINS

OPEN HILLS AND MOUNTAINS

C2	OPEN LOW HILLS
C3	OPEN HILLS
C4	OPEN HIGH HILLS
C5	OPEN LOW MOUNTAINS
C6	OPEN HIGH MOUNTAINS

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

TABLELANDS

B3c,d	TABLELANDS, MODERATE RELIEF
B4c,d	TABLELANDS, CONSIDERABLE RELIEF
B5c,d	TABLELANDS, HIGH RELIEF
B6c,d	TABLELANDS, VERY HIGH RELIEF

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

A	>80% OF AREA GENTLY SLOPING
B	50-80% OF AREA GENTLY SLOPING
C	20-50% OF AREA GENTLY SLOPING
D	<20% OF AREA GENTLY SLOPING

LOCAL RELIEF (2nd LETTER)

1	0 TO 30m (1 TO 100 ft)
2	30 TO 90m (100 TO 300 ft)
3	90 TO 150m (300 TO 500 ft)
4	150 TO 300m (500 TO 1000 ft)
5	300 TO 900m (1000 TO 3000 ft)
6	900 TO 1500m (3000 TO 5000 ft)

PROFILE TYPE (3rd LETTER)

a	>75% OF GENTLE SLOPE IS IN LOWLAND
b	50-75% OF GENTLE SLOPE IS IN LOWLAND
c	50-75% OF GENTLE SLOPE IS ON UPLAND
d	>75% OF GENTLE SLOPE IS ON UPLAND

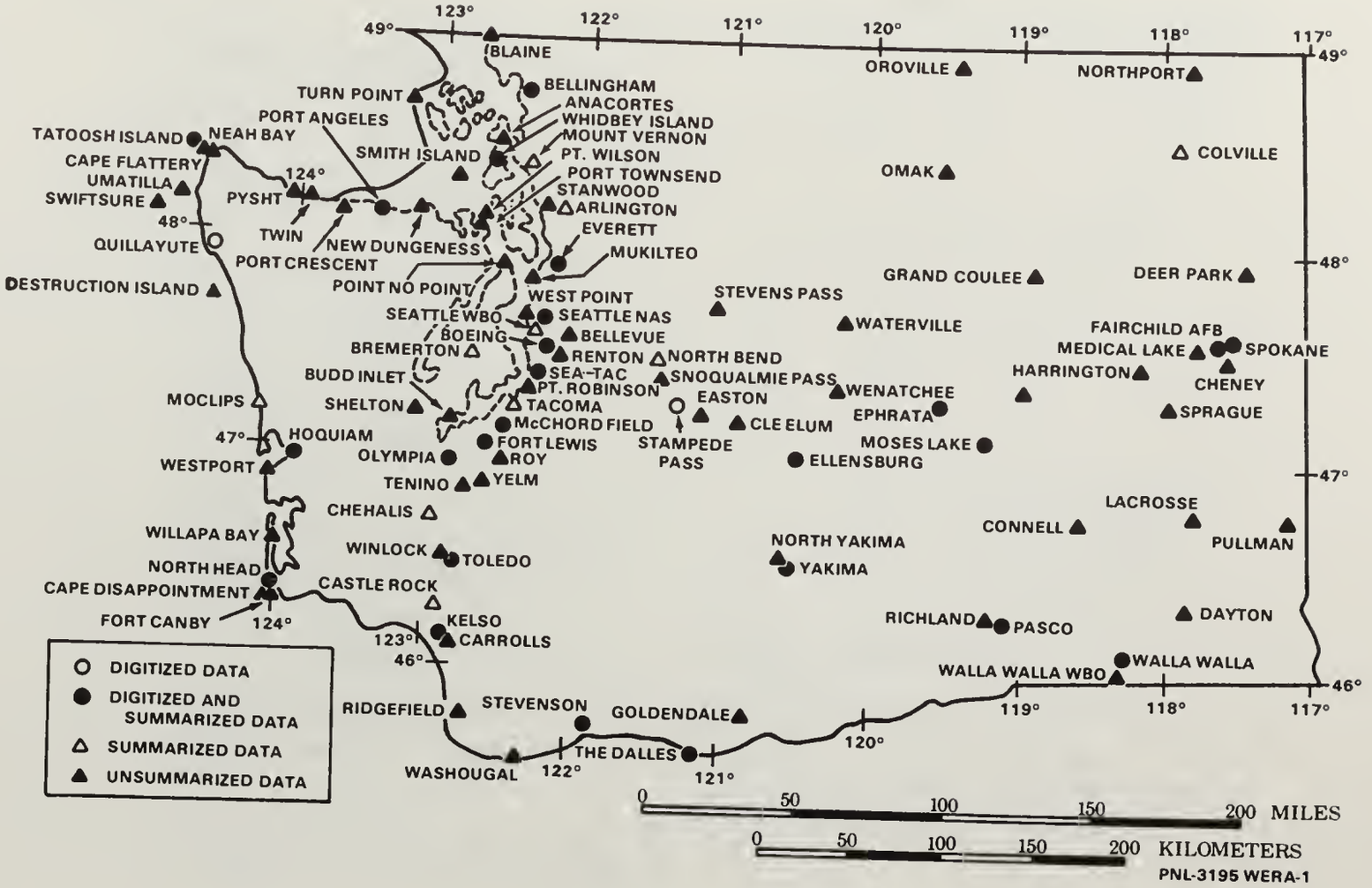


FIGURE 7.4. NCC Station Locations in Washington

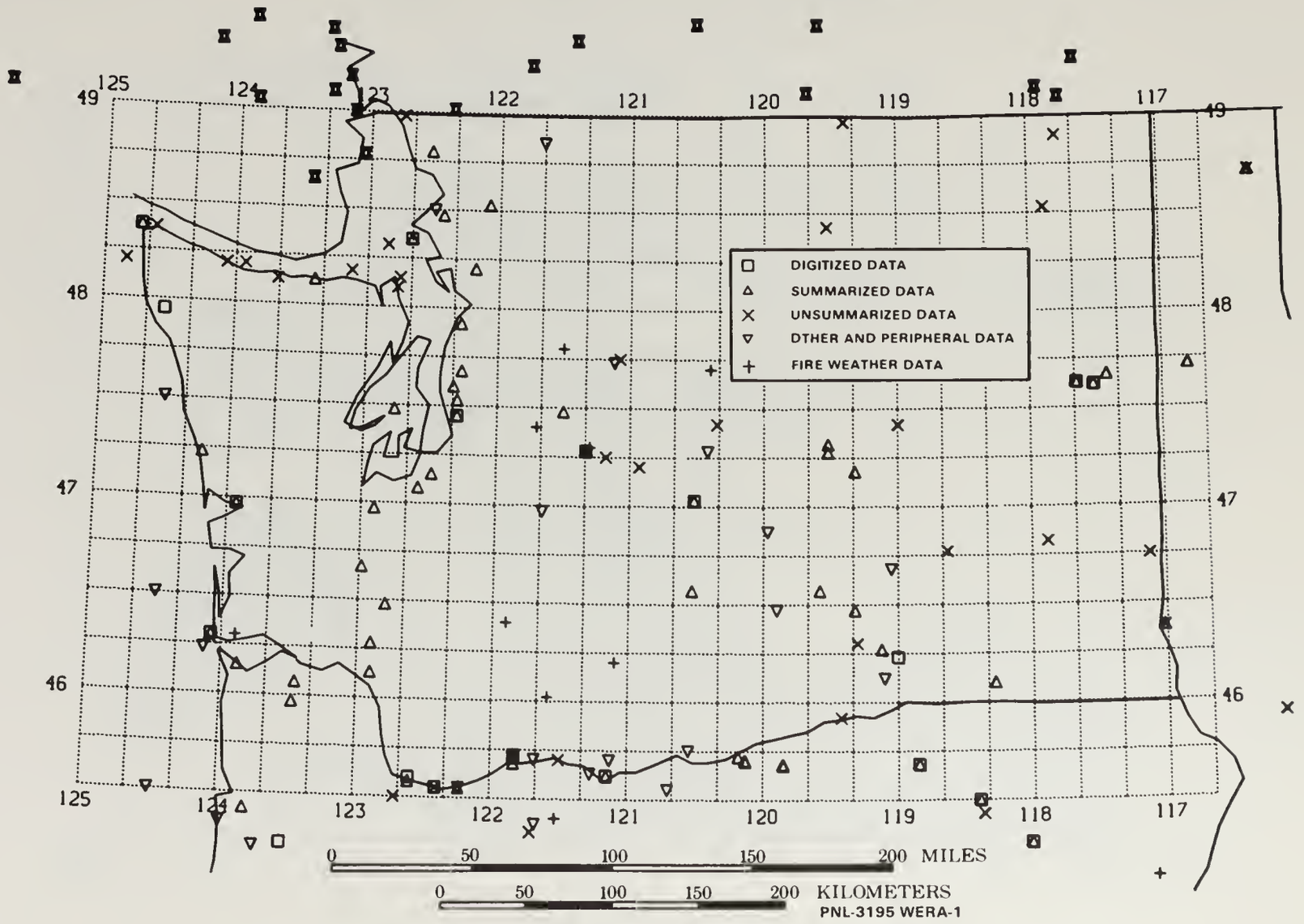


FIGURE 7.5. Locations of Stations Used in Washington Resource Assessment

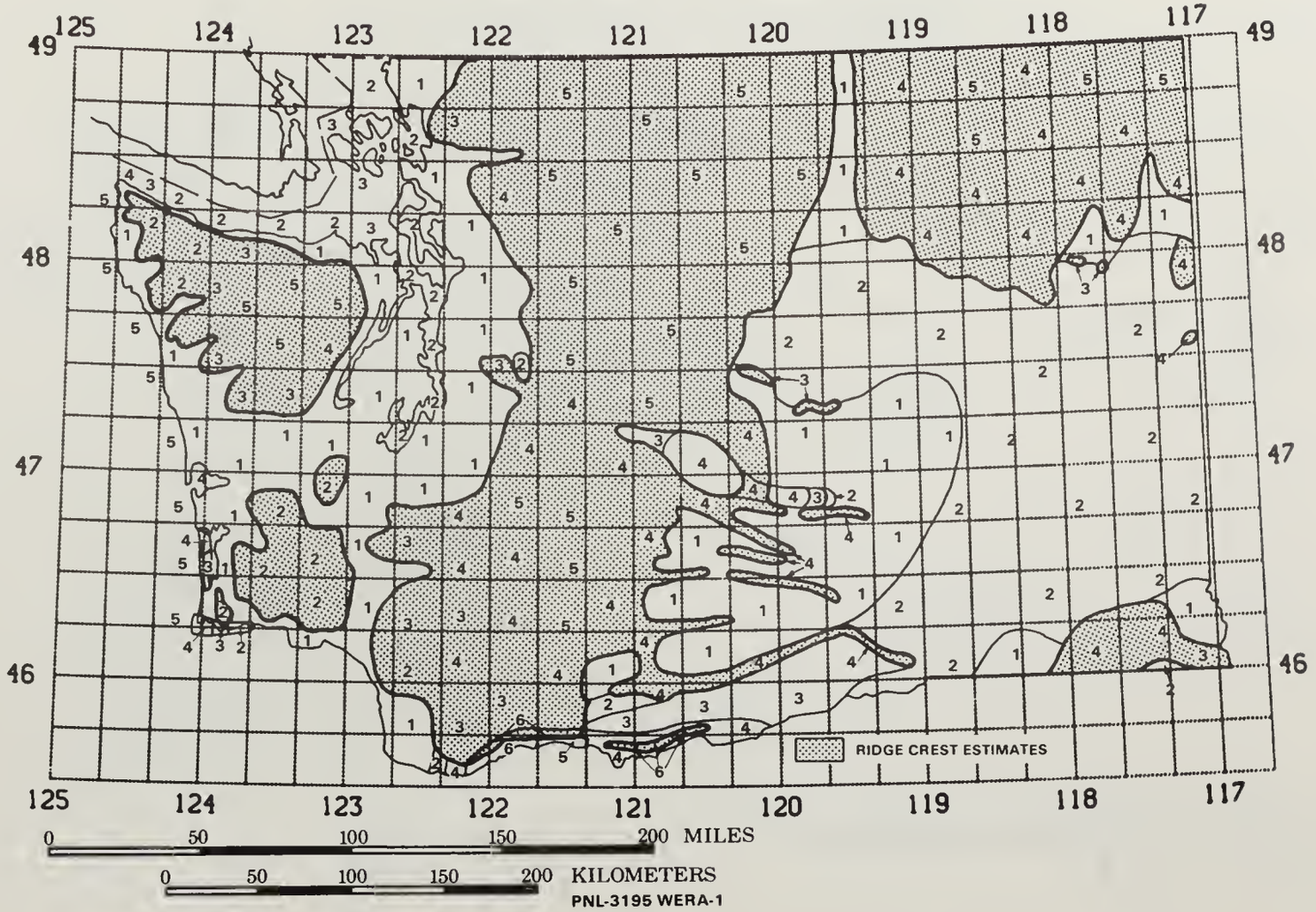


FIGURE 7.6. Washington Annual Average Wind Power

Classes of Wind Power Density at 10 m and 50 m[a]

Wind Power Class	10 m (33 ft) Wind Power Density, watts/m²	10 m (33 ft) Speed,[b] m/s (mph)	50 m (164 ft) Wind Power Density, watts/m²	50 m (164 ft) Speed,[b] m/s (mph)
1	0	0	0	0
2	100	4.4 (9.8)	200	5.6 (12.5)
3	150	5.1 (11.5)	300	6.4 (14.3)
4	200	5.6 (12.5)	400	7.0 (15.7)
5	250	6.0 (13.4)	500	7.5 (16.8)
6	300	6.4 (14.3)	600	8.0 (17.9)
7	400	7.0 (15.7)	800	8.8 (19.7)
	1000	9.4 (21.1)	2000	11.9 (26.6)

(a) Vertical extrapolation of wind speed based on the 1/7 power law.
(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

FIGURE 7.1. Areal Distribution (km^2) of Wind Power Classes in Washington

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	140,000	78.	180,000	100.
2	29,000	16.	39,000	22.
3	5,300	3.0	10,000	5.8
4	4,100	2.4	4,900	2.8
5	760	0.43	800	0.45
6	38	0.02	38	0.02
7	0	0.00	0	0.00

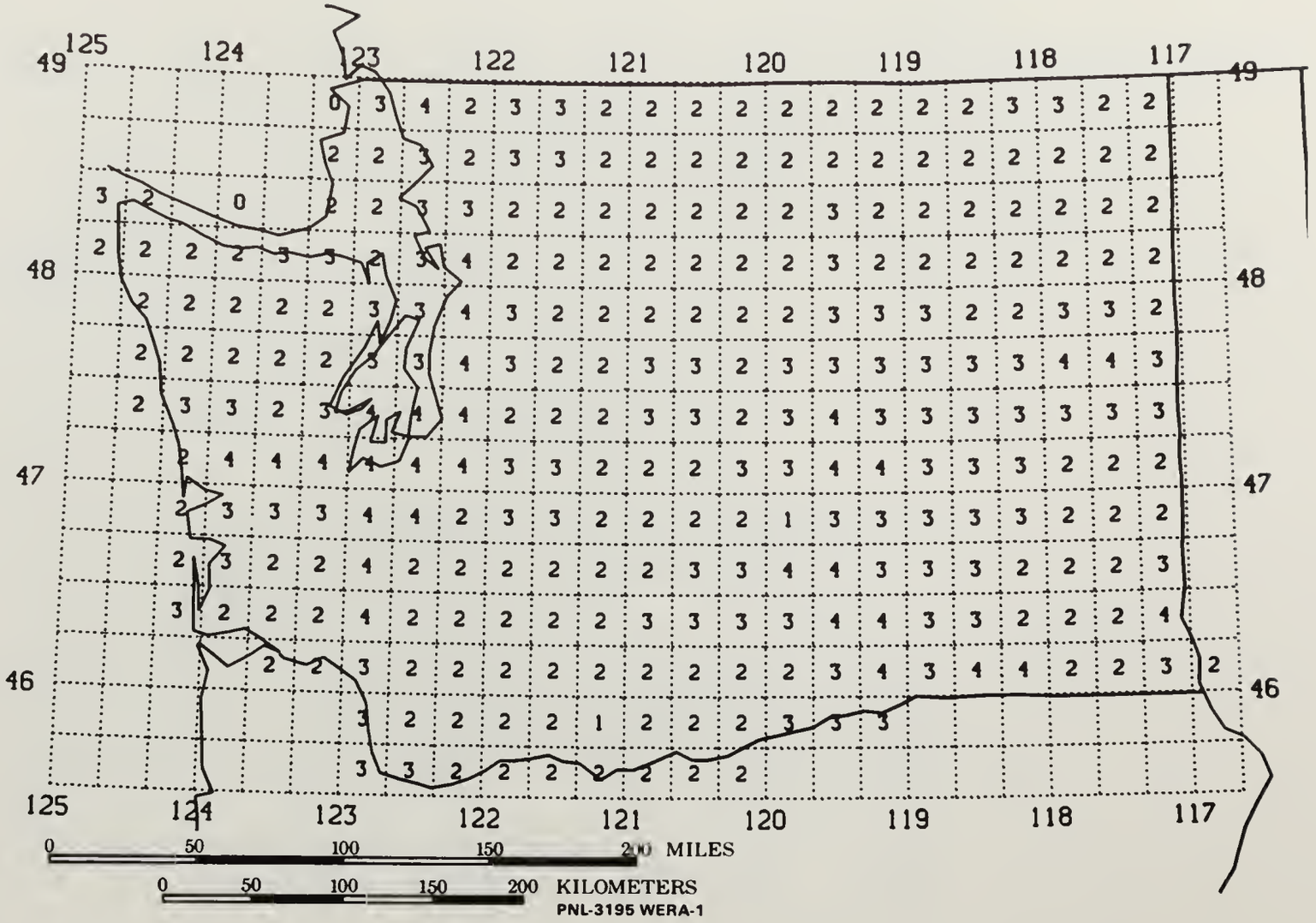
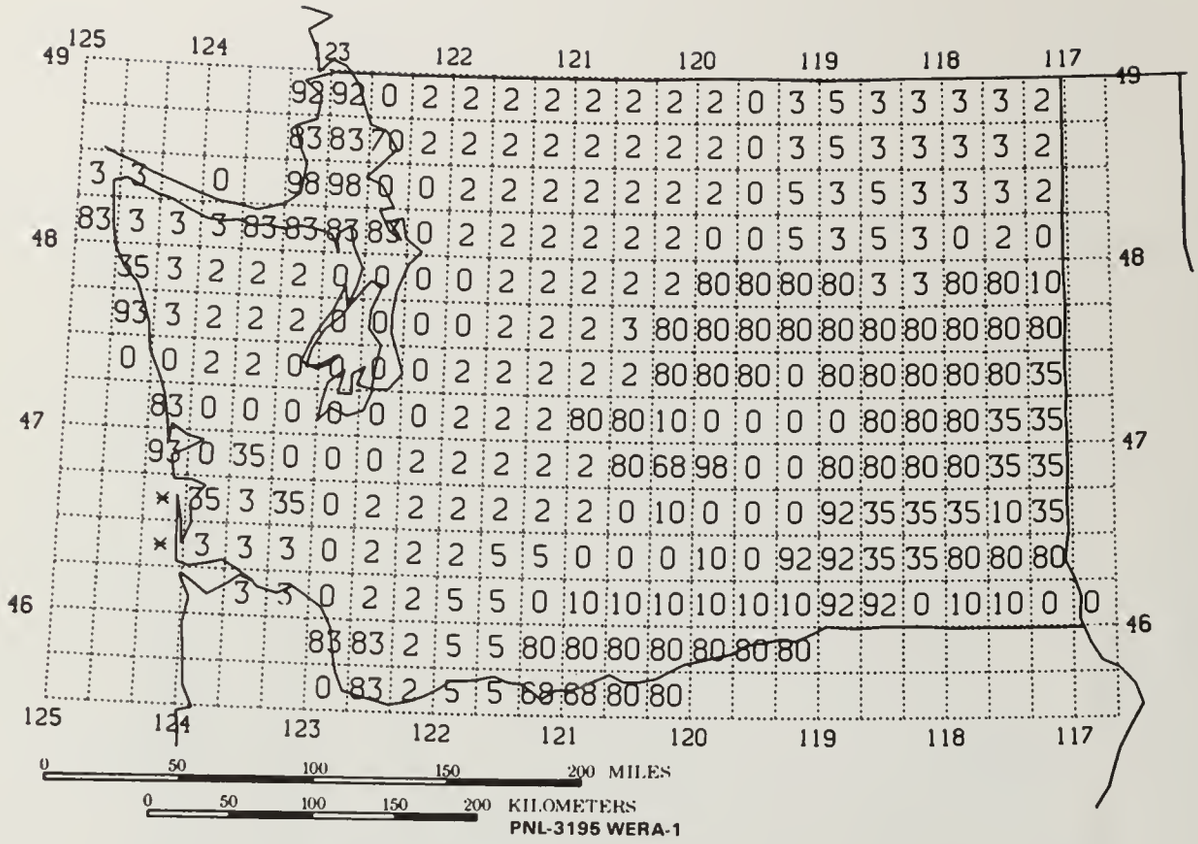


FIGURE 7.7. Certainty Rating of Washington Wind Resource

CERTAINTY RATING LEGEND

Rating	Definition
1	The lowest degree of certainty. A combination of the following conditions exists: 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	A low-intermediate degree of certainty. One of the following conditions exists: 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	A high-intermediate degree of certainty. One of the following conditions exists: 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.

Class 2



Class 3

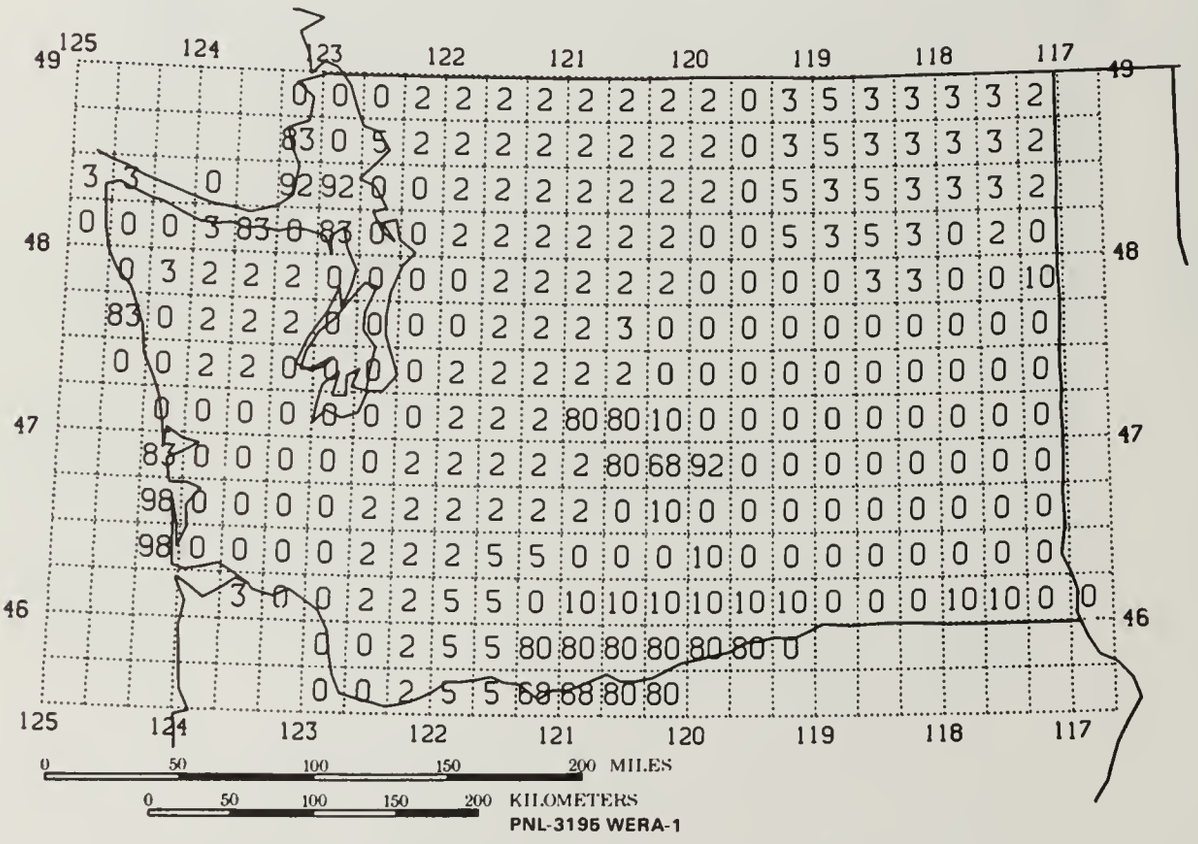
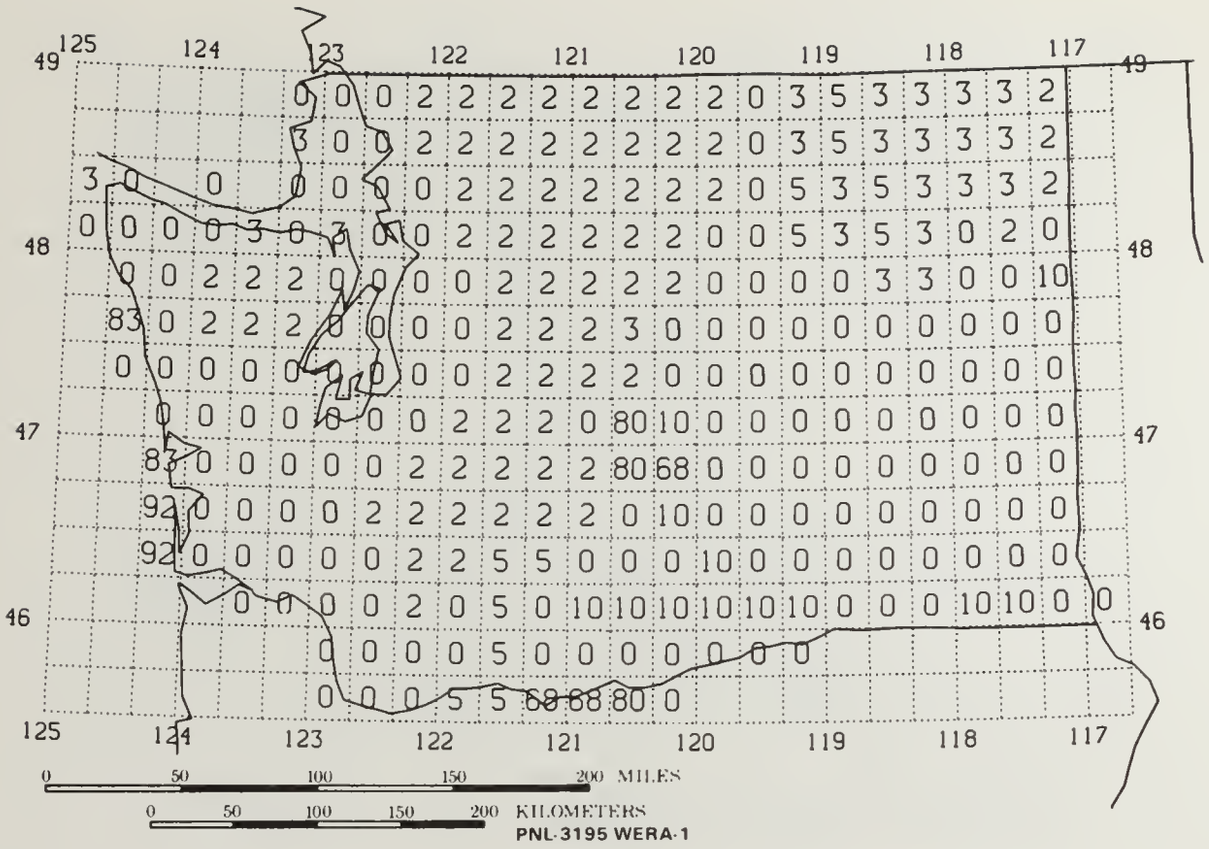


FIGURE 7.8. Areal Distribution of Wind Resource in Washington (Power Classes 2 and 3); Percent of Land Area With or Exceeding Power Class Shown.

Class 4



Class 5

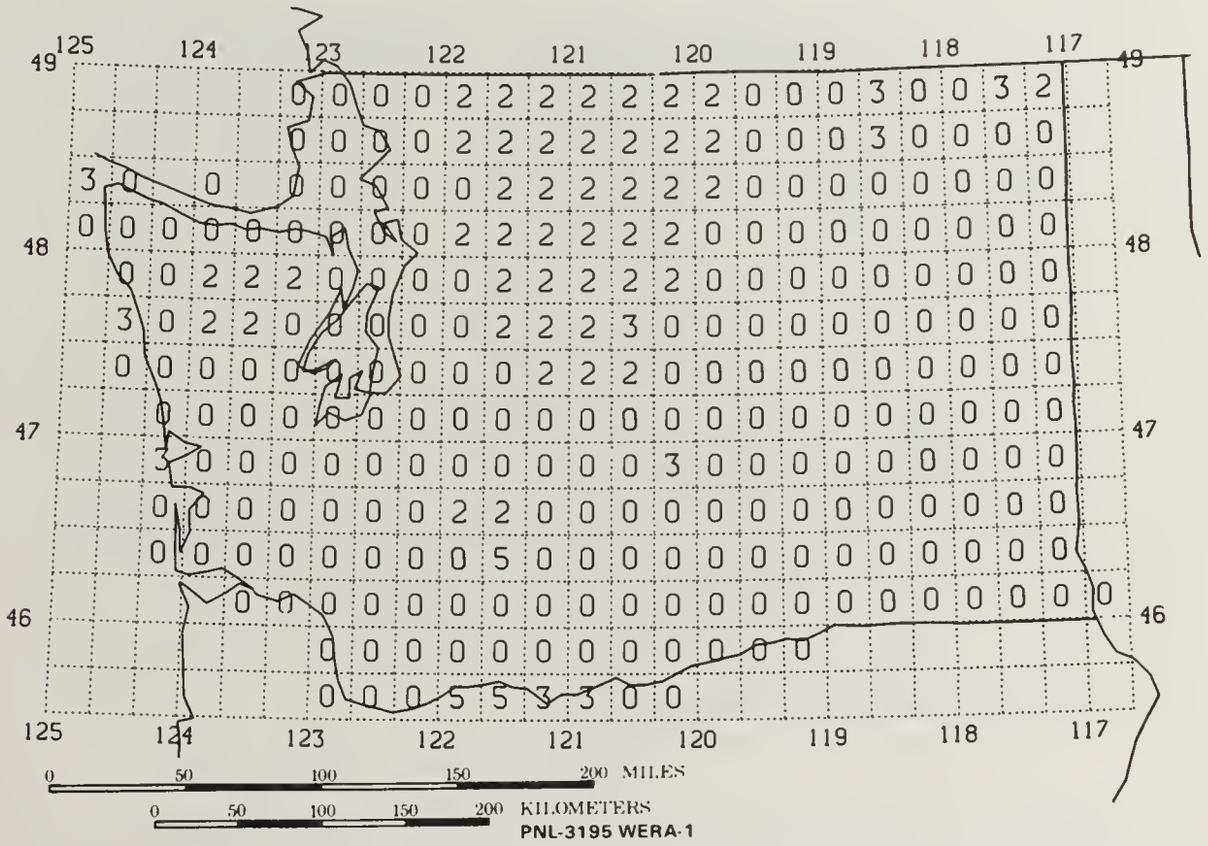
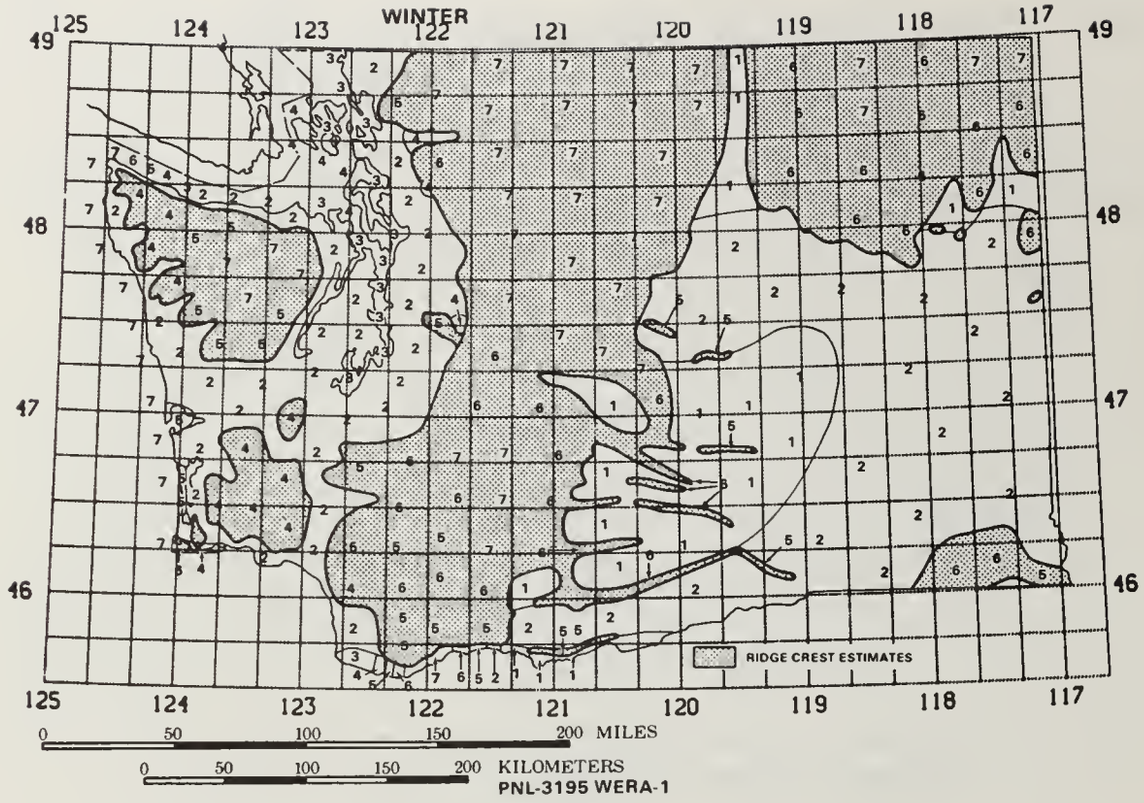


FIGURE 7.8 (Continued). Areal Distribution of the Wind Resource in Washington (Power Classes 4 and 5); Percent of Land Area With or Exceeding Power Class Shown.



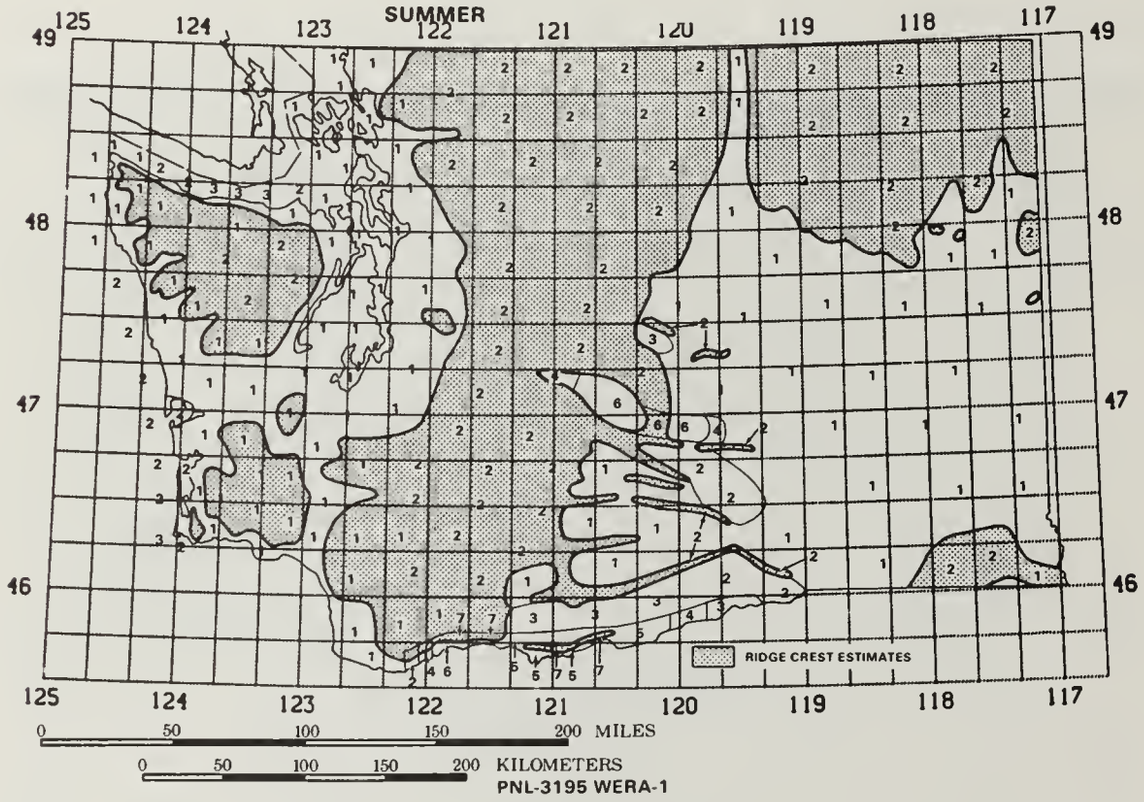
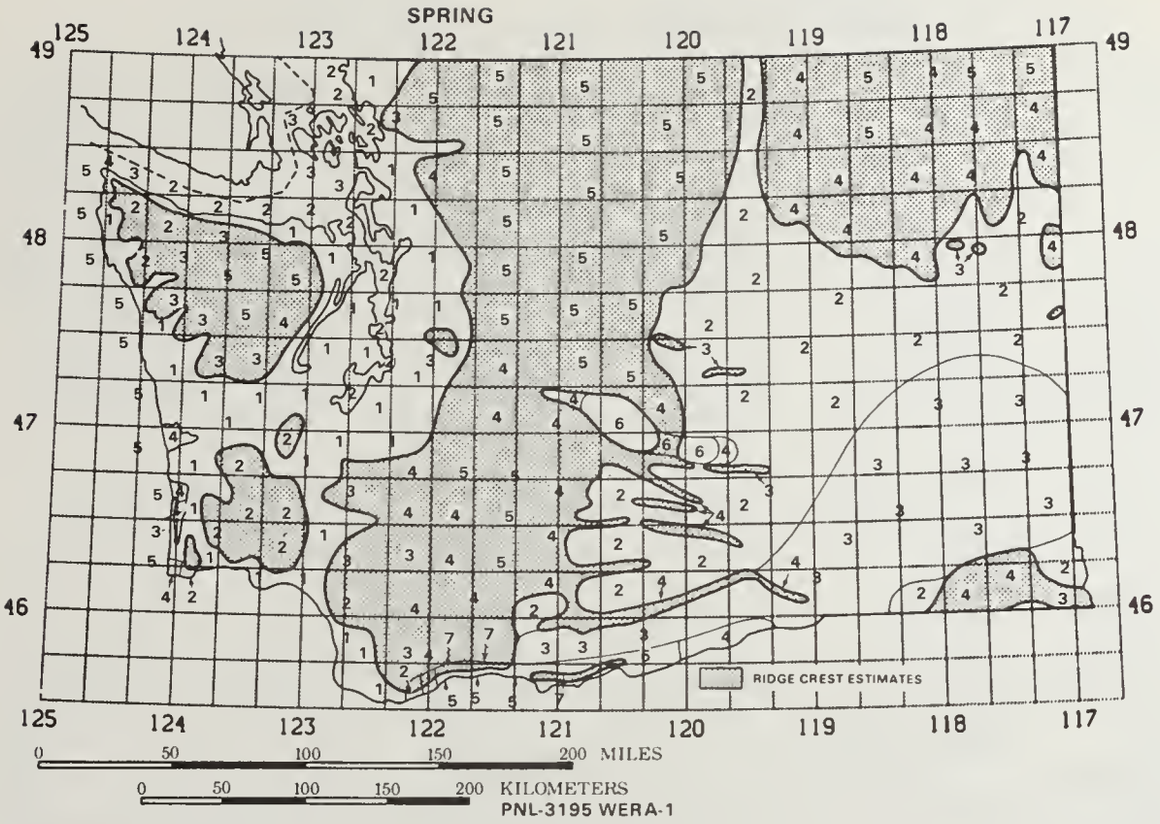


FIGURE 7.9. Seasonal Average Wind Power in Washington (Winter, Summer)



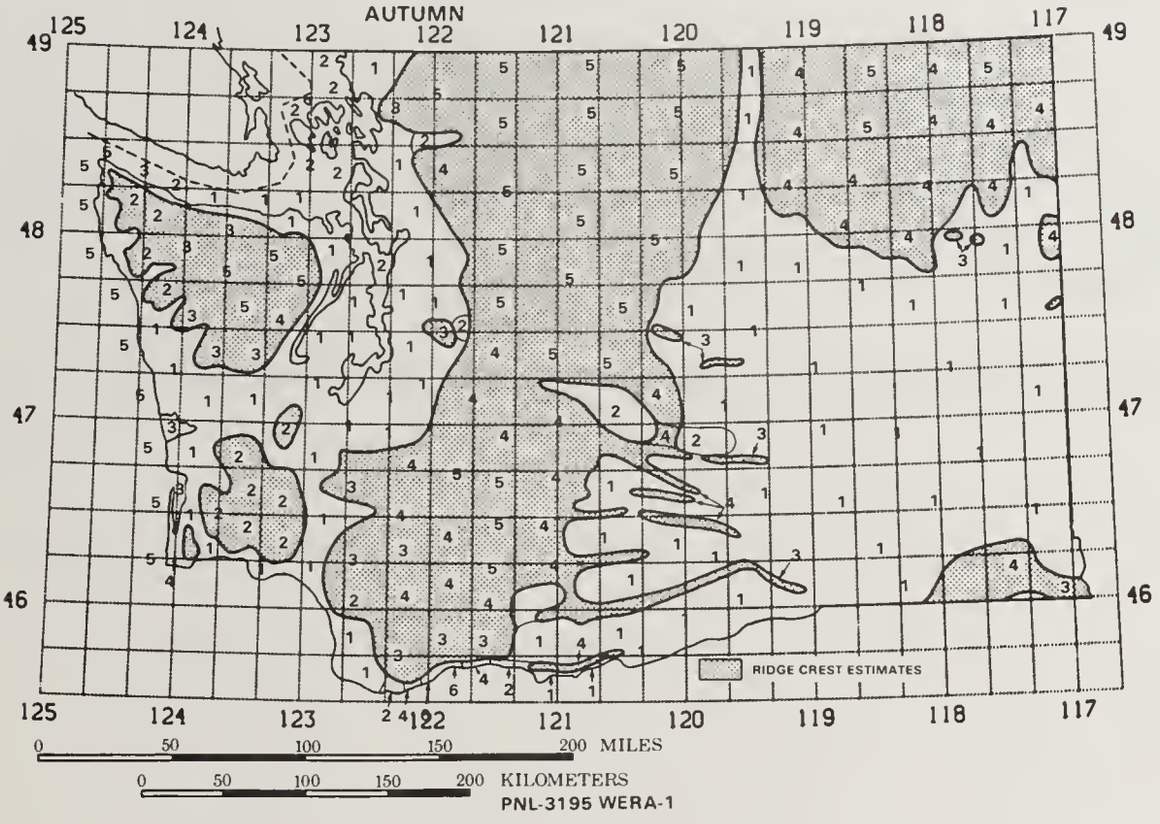


FIGURE 7.9 (Continued). Seasonal Average Wind Power in Washington (Spring, Autumn)

TABLE 7.2. Washington Stations with Graphs of the Wind Characteristics

Station	Station Name[a]	Latitude, Degrees North	Longitude, Degrees West	Elevation of Station, m	Period of Record, Month/Year	Anemometer Height, m	Annual Average Wind Speed, m/s			Annual Average Wind Power, watts/m²		
							At Anemometer Height, m	At 10 m	At 50 m	At Anemometer Height, m	At 10 m	At 50 m
Dallesport, Washington	The Dalles (Oregon) Airport	45.62	121.15	72	01/48-03/61	12.5	4.2	4.0	5.1	139	126	252
Ellensburg, Washington	Ellensburg Bowers Airport	47.03	120.52	527	06/48-12/54	18.3	4.9	4.5	5.6	279	215	429
Hoquiam, Washington	Hoquiam Bowerman Airport	46.97	123.93	8	05/53-12/58	7.9	5.3	5.5	6.9	182	201	401
North Head, Washington	North Head WBO	46.30	124.08	67	02/48-12/48	16.8	6.6	6.2	7.8	435	349	695
Pasco, Washington	Pasco NAS	46.23	119.00	131	04/45-05/46	17.1	3.6	3.3	4.2	105	83	166
Quillayute, Washington	Quillayute Airport	47.95	124.53	62	08/66-12/76	6.7	3.1	3.3	4.1	41	49	97
Seattle-Tacoma, Washington	Sea-Tac International Airport	47.45	122.30	137	11/59-12/76	6.1	3.9	4.2	5.2	67	83	165
Spokane, Washington	Fairchild AFB	47.63	117.65	743	04/58-12/70	4.6	3.0	3.3	4.2	43	60	120
Spokane, Washington	Spokane International Airport	47.62	117.52	721	11/57-12/76	6.1	4.2	4.5	5.6	83	103	205
Stampede Pass, Washington	Stampede Pass WBO	47.28	121.33	1209	01/53-12/76	9.4	5.3	5.3	6.7	144	148	294
Stevenson, Washington	Stevenson WBO	45.72	121.83	97	01/48-04/52	4.9	6.4	7.1	8.9	386	525	1047
Tatoosh Island, Washington	Tatoosh Island WBO	48.38	124.73	35	01/48-12/64	19.2	6.7	6.1	7.7	443	335	668
Whidbey Island, Washington	Whidbey Island NAS	48.35	122.67	10	05/55-06/59	17.7	4.5	4.2	5.3	169	132	264

[a]CAA-Civil Aeronautics Administration Facility; NAS-Naval Air Station; WBO-Weather Bureau Office.

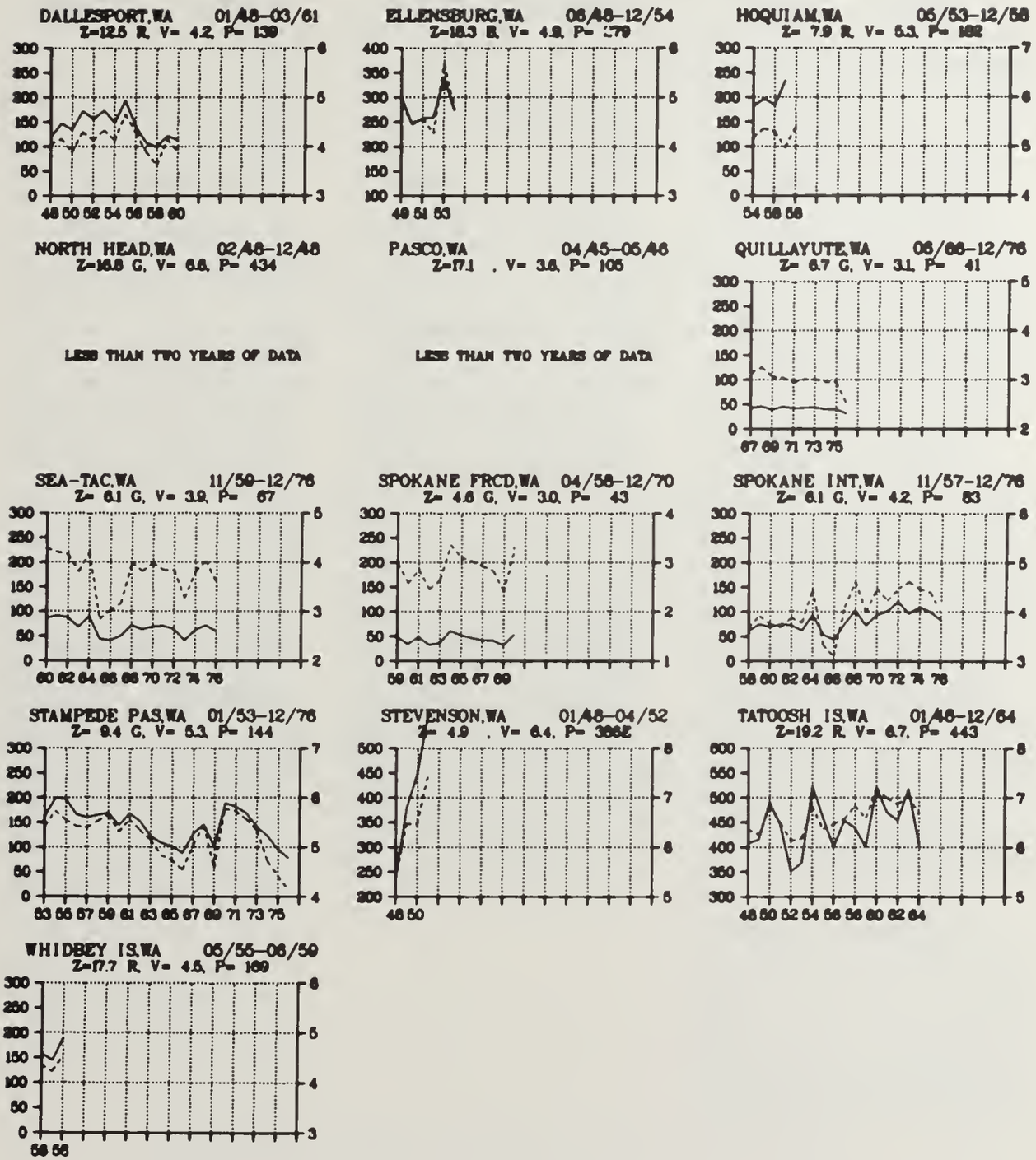


FIGURE 7.10. Interannual Wind Power and Speed for Washington

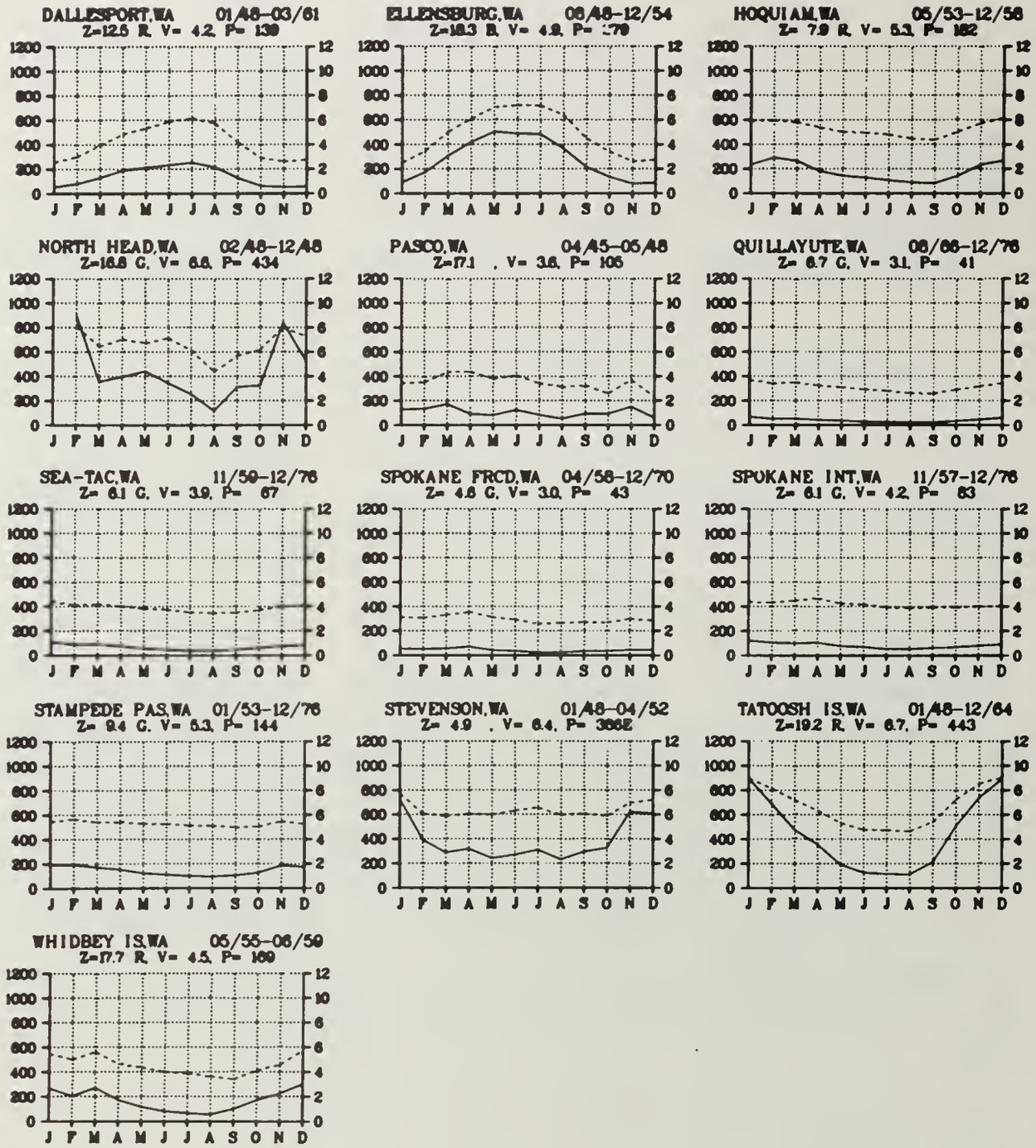


FIGURE 7.11. Monthly Average Wind Power and Speed for Washington

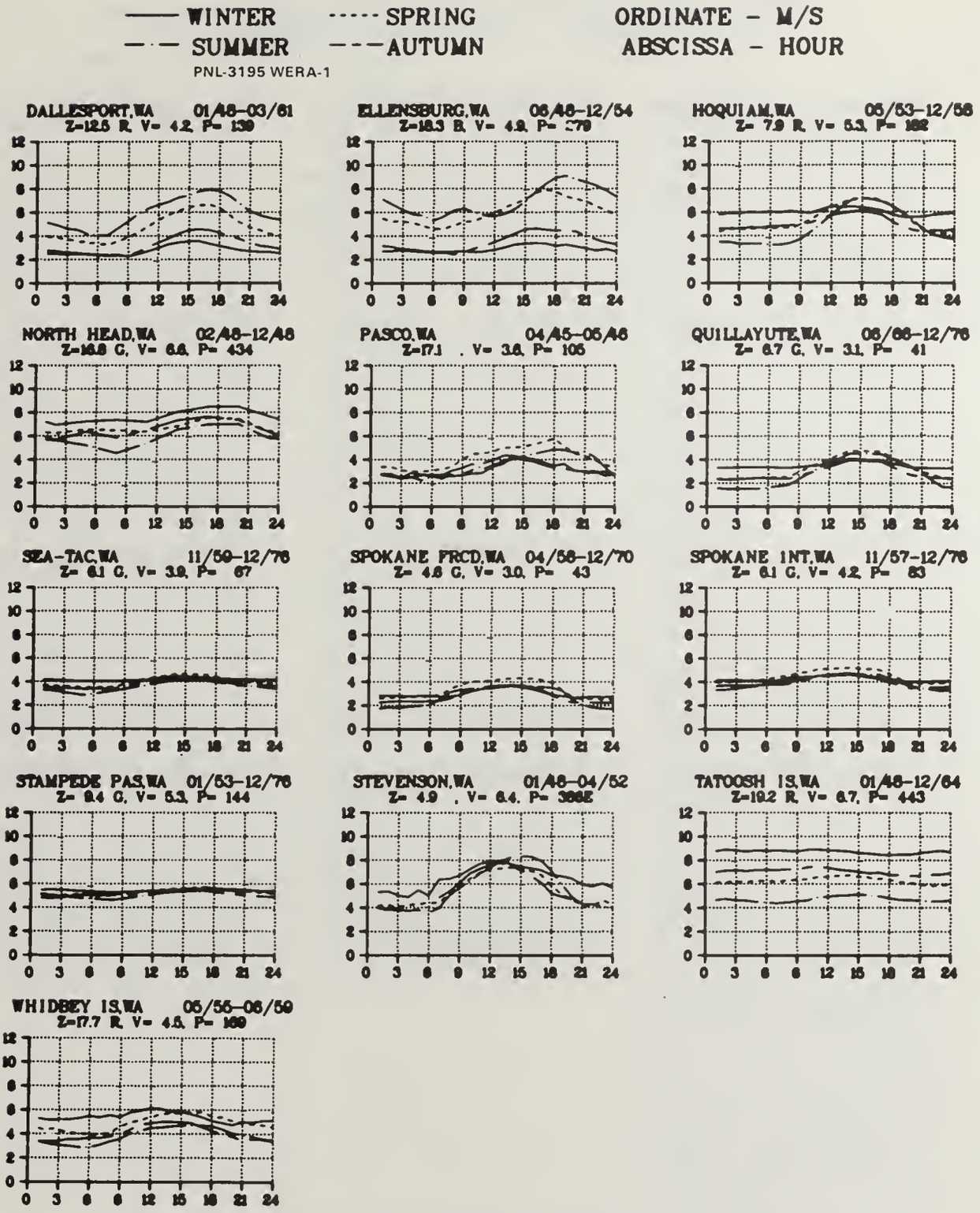


FIGURE 7.12. Diurnal Wind Speed by Season for Washington

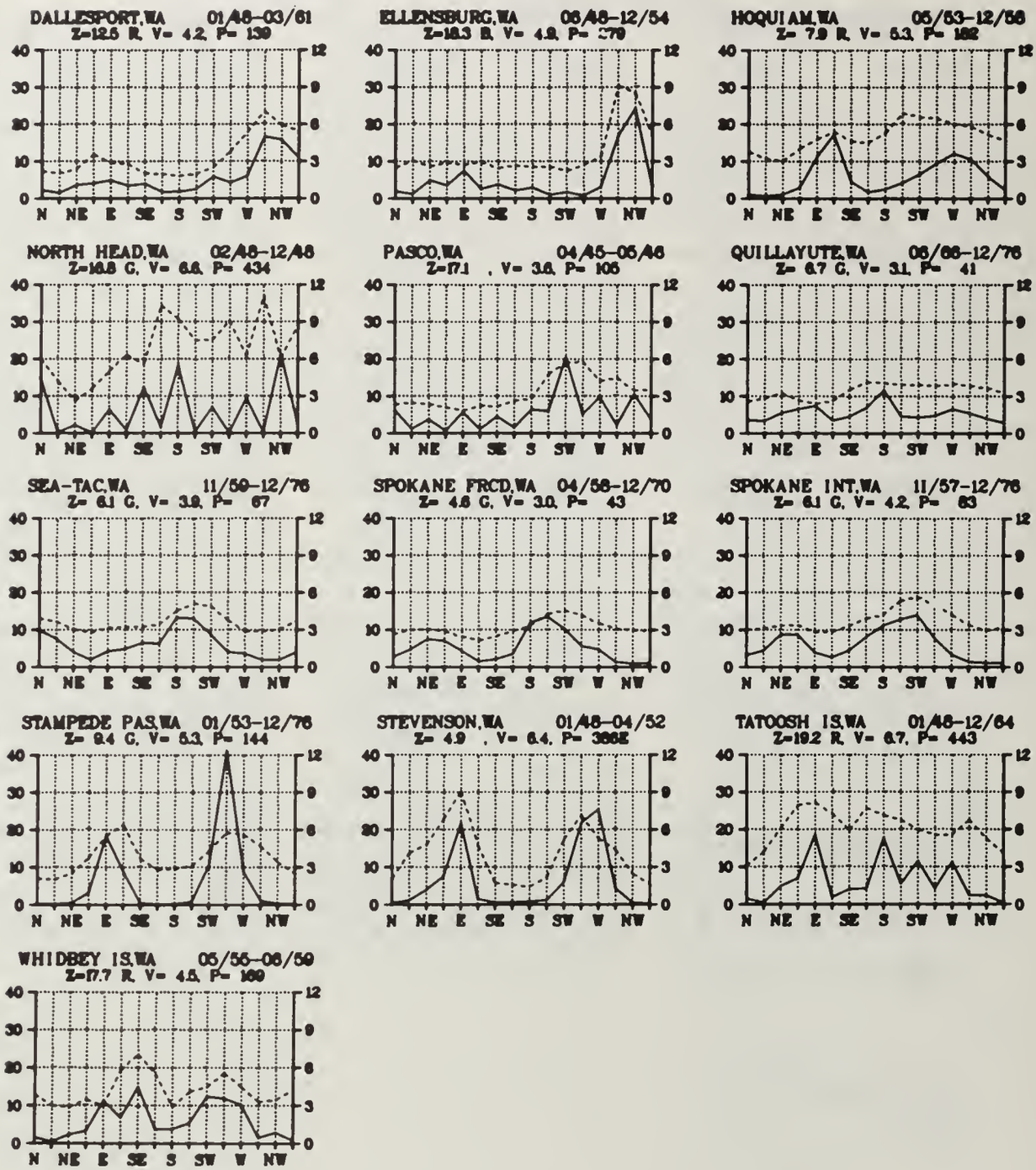


FIGURE 7.13. Directional Frequency and Average Speed for Washington

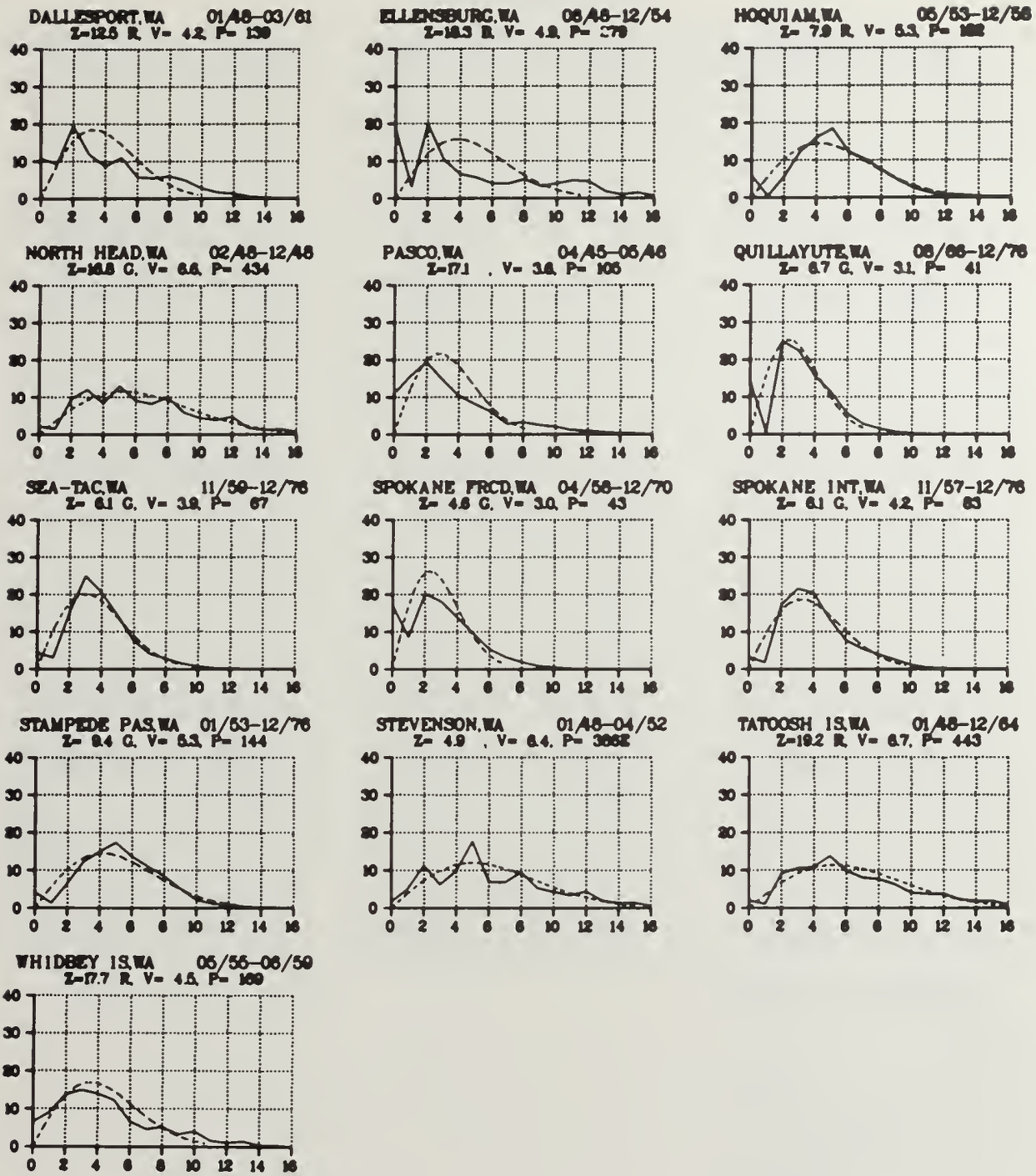


FIGURE 7.14. Annual Average Wind Speed Frequency for Washington

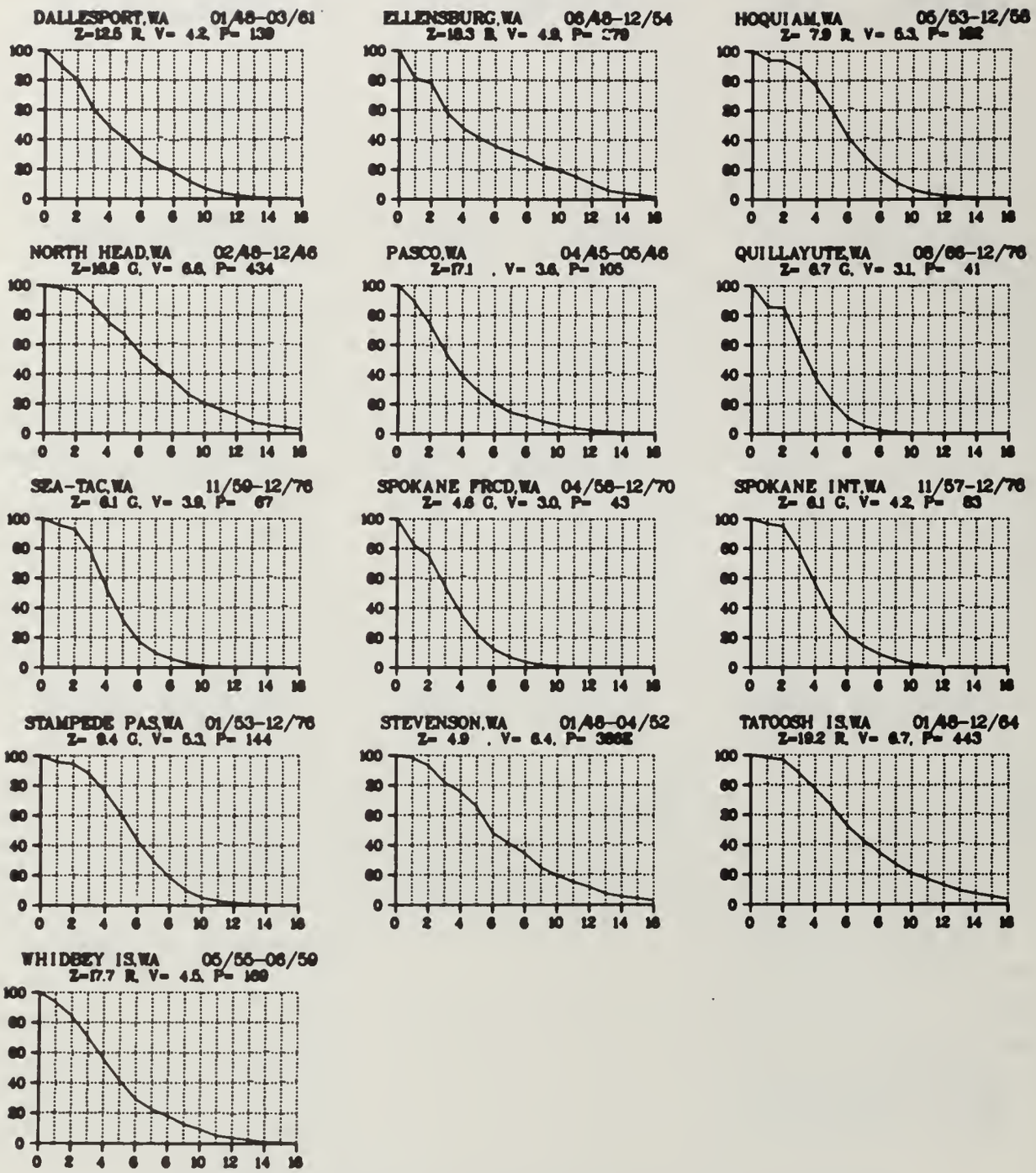


FIGURE 7.15. Annual Average Wind Speed Duration for Washington

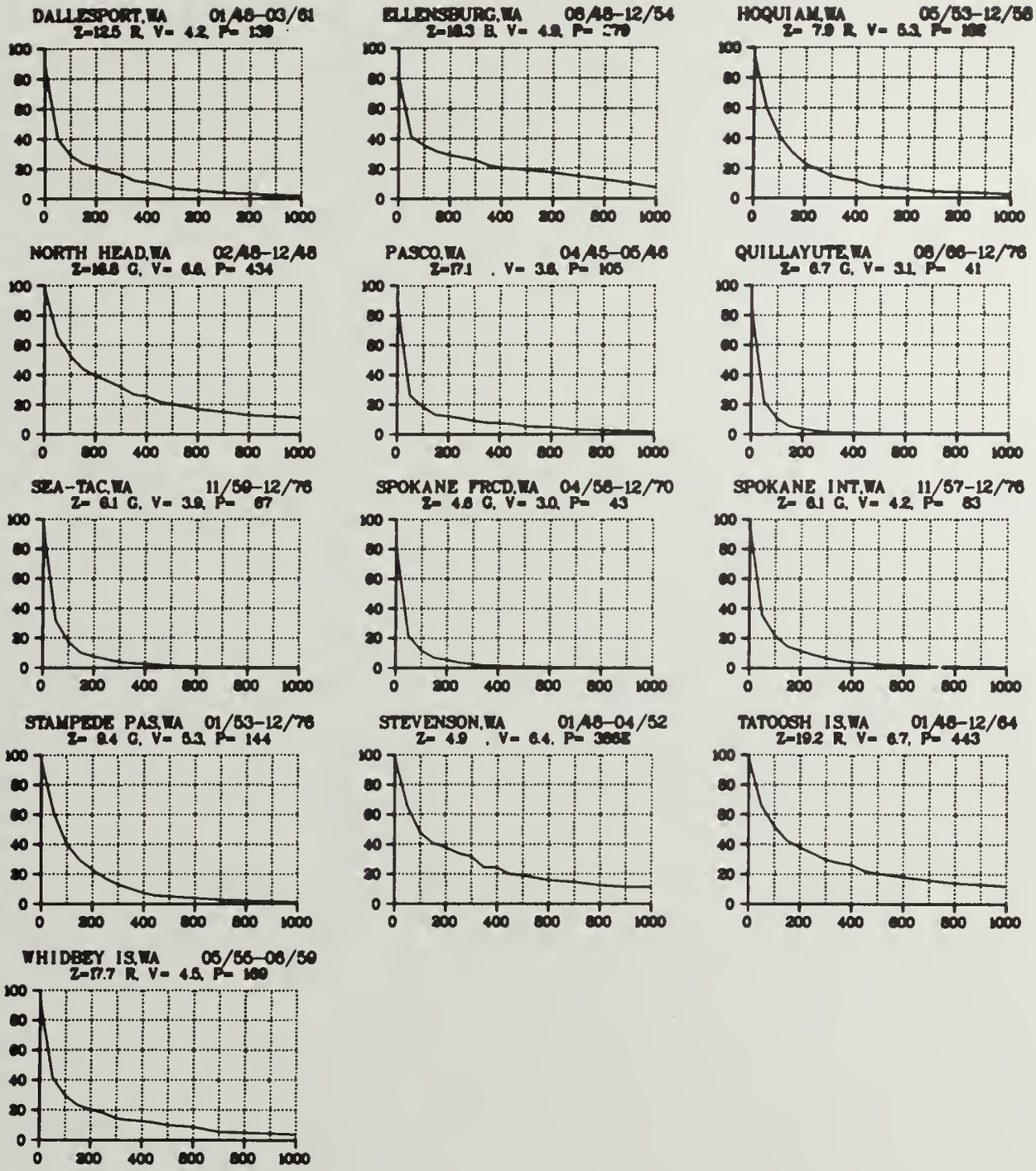


FIGURE 7.16. Annual Average Wind Power Duration for Washington

WYOMING

CHAPTER 8: WYOMING

Wyoming covers an area of 253,597 km^2 (97,914 mi^2). With a population of 332,416 in 1970, it is the least populated state in the Northwest. Most of the population resides in the windy corridor of southern Wyoming, which extends from Evanston eastward to Casper and Cheyenne, the largest cities in Wyoming (Figure 8.1). Yellowstone National Park and Grand Teton National Park are located in the northwestern corner of the state.

Most of Wyoming is either mountains or arid plains and basins. The northwestern part of the state is very mountainous and includes the Wyoming, Wind River, and Absaroka Ranges, which are all part of the Rocky Mountains (Figures 8.2 and 8.3). Much of this rugged mountainous region has been designated as wilderness and primitive areas. The Bighorn Mountains in northcentral Wyoming are separated from the main chain of the Rockies by the Bighorn River basin. The plains of southern Wyoming form a gap, 100 to 150 km (60 to 90 mi) wide, in the Rocky Mountains. This gap is a natural corridor for the prevailing strong westerly winds. In southeastern Wyoming, the Medicine Bow and Laramie Mountains extend northward from the Colorado Rocky Mountain ranges.

Existing summarized or digitized wind data from the National Climatic Center (NCC) are available for 20 stations in Wyoming (Figure 8.4). Unsummarized NCC data are available for 23 additional stations, but the data from many of these stations were of very limited value (see Chapter 1). In the southern Wyoming wind corridor, the stations are mostly distributed along the interstate highway between Evanston and Cheyenne. Fire weather data are abundant in the mountainous regions, but only those stations for which more than 70% of the single daily observations during the fire season exceeded 3.5 m/s are used. Only 5 stations satisfy this criterion (Figure 8.5). Wind data have been collected for numerous other sites in Wyoming (Marwitz and Gilkey 1979); however, few of these data are summarized.

8.1 ANNUAL AVERAGE WIND POWER

The annual average wind power is estimated to be class 4 and 5 throughout the windy corridor in southern Wyoming (Figure 8.6) extending from the Utah border on the west to the Nebraska border on the east. The map values for the high wind resource areas (class 4 and above) mostly refer to open plains and tablelands, except for the shaded areas which represent ridge crest estimates. However, numerous smaller hilltops and ridges (not shown on the wind power maps) in the southern Wyoming plains may have one or even two classes greater wind power than the open plains, especially if the nearby terrain features enhance the wind speed. On the other hand, sheltered areas in southern Wyoming (e.g., where nearby terrain shields the site from the prevailing strong winds) may have one or two classes lower wind power than the map value. Existing data and meteorological and topographical features indicate that class 5 areas may exist in the gaps between the shaded ridges in south-central Wyoming (Elliott 1979a). No doubt other class 5 or higher wind corridors of varying size exist in southern Wyoming. In some areas, eolian features give evidence of strong winds (Kolm and Marrs 1977).

Because the data are confined to a narrow east-west belt in southern Wyoming (see Figure 8.5), the north-to-south extent of the strong-wind corridor in southern Wyoming (the class 4 zone) is uncertain. However, because the atmospheric forces that produce the strong westerly winds in this region are predominantly associated with large-scale surface pressure gradients and strong winds aloft, the class 4 wind power is estimated to exist throughout the width of the gap in southern Wyoming. The gap is aligned parallel to the direction of the prevailing strong westerly winds. The relatively low ridges in southwestern corner of the state (north of Evanston) and the Laramie Mountains in the southeast apparently offer little resistance to strong westerly winds, as locations in the lee side of these mountains usually also indicate prevailing strong westerly winds.

Near the Colorado border, from the Medicine Bow Mountains westward to the Uinta Mountains (110°W longitude) on the Utah border, the wind power is estimated to be class 3 because of greater terrain shielding. However, no data were available within this area. The class 3 area in southeastern Wyoming is in the North Platte River valley.

Wind power in the sheltered basins of west-central Wyoming decreases abruptly northward of the southern Wyoming wind corridor. For example, Big Piney, Lander and Riverton have only class 1 wind power. Higher wind power may exist in small areas affected by mountain valley drainage winds.

The southern end of the Bighorn Basin also has class 1 wind power. However, in the northern end of this basin, near Powell, frequent moderate-to-strong northwest winds

may be channeled through the gap (about 30 km wide, north of Powell) between the Bighorn Mountains and Absaroka Range. Strong west-to-southwest winds at Cody are apparently associated with the same weather conditions that produce the strong winds in the Livingston and Whitehall wind corridors of Montana during the colder months. Small areas near the mouth of the Shoshone River valley and other large valleys may have class 5 or 6 wind power.

In northeastern Wyoming, the upland areas and open plains are estimated to have class 3 wind power, based on the limited data in this part of the state. Data from stations near the base of the east slopes of the Bighorn Mountains indicate class 2 wind power within 30 to 50 km (20 to 30 mi) of the base of the mountains. Some of the well-exposed hilltops and ridges in northeastern Wyoming (not the shaded mountainous areas) may have a class higher wind power than the map values, whereas sheltered areas and valleys such as the Powder River and Belle Fourche River valleys may have wind power one or two classes lower than the map value.

In the mountainous areas of Wyoming, exposed mountain summits and ridge crests in the Rocky Mountains are estimated to have class 5 or higher wind power. However, much of the rugged mountainous area in northwestern Wyoming is generally inaccessible, whereas the less-rugged mountains in southwestern and southeastern Wyoming, such as the Laramie, Medicine Bow, Shirley, and Green Mountains, are generally more accessible. Exposed crests in the Black Hills in northeastern Wyoming are estimated to have at least class 4 wind power.

8.1.1 Certainty Rating of the Wind Resource

Certainty ratings of the wind power estimates for Wyoming vary from 1 to 4 (Figure 8.7). Several areas in southern Wyoming have class 4 or 5 power with a high certainty, e.g., areas near Fort Bridger, Laramie, Cheyenne, Douglas, and Casper. Most of the wind data stations in the southern Wyoming wind corridor between Evanston and Medicine Bow are located in a narrow east-west belt near Interstate 80; and thus, the north-south extent of the resource is uncertain. This is shown in certainty ratings that decrease from 3 (high-intermediate) along the narrow belt from which data were taken to 1 (low) along the perimeter of the corridor or in areas where topographic shielding may occur. The wind power estimates for the plains, tablelands, and open low hills of northeastern Wyoming mostly have certainty ratings of 2 and 3. The area around the one well-exposed site in northeastern Wyoming with wind data was given a high certainty (4). No wind data were available in any of the areas with low-intermediate certainty ratings in eastern and southern Wyoming.

The certainty ratings in the sheltered basins of northwestern Wyoming varied from high to low. Cells with low certainty ratings represent areas with no wind data where large geographical variations in wind power may occur, e.g., near mountain valley drainages.

Although no year-round data were available from exposed sites in nonmountainous terrain, the mountain summit and ridge crest estimates are given a certainty rating of 2 because upper-air wind data were used to approximate the power in these areas.

8.1.2 Areal Distribution

The southern Wyoming wind corridor occupies about 50% of the land area of the state and contributes almost all of the 30% of land area of the state associated with class 4 and higher wind power (Table 8.1 and Figure 8.8). In contrast, the mountainous areas with class 4 and higher wind power cover about 22% of the state but contribute only about 0.5% to power classes 4 and above. The plains of the Medicine Bow and Casper wind corridors contribute significantly to power class 5 and higher as is seen in Figure 8.8.

The area of class 7 wind power is associated with the plains of the southern Wyoming wind corridor. Here it is assumed that a small percentage of the land area of the plains, e.g., prominent hills or ridges on which speedup effects enhance the wind power, has a higher wind power than the plains (see Section 1.9).

8.2 SEASONAL WIND POWER

Wind power maps for each season are shown on facing pages in Figure 8.9. Winter is the season of maximum wind power throughout the mountains of Wyoming and in the southern Wyoming wind corridor. Spring is the season of maximum wind power in northeastern Wyoming and in the sheltered basins and valleys of the Rocky Mountains, except near the outlets of long mountain valleys where the wind power is usually greater in winter. Summer is the season of lowest wind power for the entire state.

8.2.1 Winter

In winter, class 6 and 7 wind power is estimated throughout the southern Wyoming wind corridor (Figure 8.9). The prevailing strong wind directions are generally south-

west to west-northwest. In northeastern Wyoming, winter wind power appears to gradually decrease from class 6 and 7 near Casper to class 3 about 100 km (60 mi) northeast of Casper. Sheltered basins in the Rockies indicate only class 1 or 2 wind energy, even though the wind energy aloft on ridge crests is considerably higher. Hilltops and ridges in these basins may have substantially higher wind energy than the basin, especially in the winter. Also, outlets of long valley drainages where the winds are channeled down from the mountains may have considerably greater wind power than the basin; for example, Cody in northwestern Wyoming has class 5 winter wind power. In mountainous areas, winter wind power is estimated to be class 6 and 7 on exposed mountain summits and ridge crests throughout the state, as indicated by the upper-air mean wind speeds and limited wintertime data collected on mountain summits in the Rockies.

8.2.2 Spring

In spring, the plains east of the Laramie Mountains and the Medicine Bow corridor are estimated to have class 5 power (Figure 8.9). In the southern Wyoming corridor from Evanston east to the Laramie Mountains, average wind speeds generally decrease from March through May, as the pressure gradient forces weaken and the winds aloft decrease. Ridge crests and mountain summits in the Rockies are estimated to have class 5 or 6 power in the spring.

8.2.3 Summer

In summer, class 3 is the highest wind power anywhere in the state and is estimated to occur only on exposed ridge crests and mountain summits (Figure 8.9). However, a few of the windiest fire weather stations in northwestern Wyoming indicated wind powers of class 4 and 5, based on one afternoon observation per day during the fire weather season. At these stations, the free air flow may be accelerated by local topography.

8.2.4 Autumn

In autumn, class 3 power is estimated for most of the plains area of southern and eastern Wyoming, except for the windier gaps and corridors which have at least class 4 power. Exposed mountain summits and ridge crests are estimated to have class 5 and 6 power in autumn, with wind power increasing from September through November. The basins in northwest Wyoming indicate only class 1 power, except for the Cody area and the northern portion of the Bighorn Basin. As in winter, valley drainage outlets may have higher wind power than the basins.

8.3 FEATURES OF SELECTED STATIONS

Table 8.2 gives the location and annual wind speed and power density of nine stations in Wyoming. Graphs of other features of the wind resource are shown in Figures 8.10 to 8.16. Eight of these stations are in the southern Wyoming wind corridor, extending from Fort Bridger east to Cheyenne and north to Douglas and Casper.

Casper Airport is located downwind of a gap between the Laramie Mountains and Rattlesnake Hills and appears to have excellent exposure to the strong prevailing southwesterly winds, which are channeled through the gap. The city of Casper appears to be more sheltered than the airport from these strong winds by nearby Casper Mountain.

Cheyenne Airport, located on the high plains in southeastern Wyoming, appears to be representative of exposed sites in that area.

Douglas is situated in the North Platte River plain on the leeward side of the Laramie Mountains. Although Douglas is slightly lower in elevation than much of the surrounding region, it does not appear to be significantly sheltered from the prevailing strong winds, as the estimated wind power for Douglas is almost as high as for Casper.

Fort Bridger station is located on a plateau in southwest Wyoming about 100 m (300 ft) higher in elevation than the town of Fort Bridger and appears well exposed to the winds. This site should be quite representative of the wind characteristics for exposed areas in that region of Wyoming.

Laramie rests in the lowlands between the Medicine Bow and Laramie Mountains; however, the wind data indicate that this area is not as sheltered as might be expected. The estimated 10 m (33 ft) wind power for Laramie is only slightly lower than that for Cheyenne.

Moorcroft is located in the Belle Fourche River valley in northeastern Wyoming. Because of its relatively low elevation, the wind power at Moorcroft is expected to be about one class lower than that of the uplands of northeastern Wyoming. Only two and one-half years' data were available for this site. One year's data from an upland site near Wyodak, about 30 km (20 mi) west of Moorcroft, indicated one class higher wind power than Moorcroft.

Rawlins and Sinclair are located about 10 km (6 mi) apart in southcentral Wyoming; yet, the data showed a dramatic difference in wind power between these two sites (see

Table 8.2). The Rawlins Airport, located 3 to 5 km (2 to 3 mi) east of some higher hills, may be somewhat sheltered from the prevailing strong westerly winds. A very high frequency of calms (20%) observed at the Rawlins Airport suggests some terrain shielding. On the other hand, Sinclair's estimated wind power at 10 m (424 watts/m^2) may be considerably overestimated. The anemometer height listed for Sinclair in the National Wind Data Index (Changery 1978) is 29 feet above ground with a roof top exposure. However, Sinclair's station history data for 1940 lists an anemometer height of 59 feet above ground on a beacon tower. If the latter also applies over the period 1948 to 1951, then the 10 m adjusted wind power at Sinclair would be 296 watts/m^2 instead of 424 watts/m^2. Digitized records for only three complete years are available for Sinclair, and the interannual variability of the wind power was very large during this period (Figure 8.10). Thus, the wind data presented here for Rawlins and Sinclair should be used with caution, since the representativeness and reliability of the wind data are questionable for these two stations.

The Rock Springs Airport is located in a shallow basin with hills and ridges 10 to 15 km (6 to 10 mi) away in nearly all directions. The airport appears to be somewhat sheltered from the prevailing strong westerly winds by hills and ridges to the west, which are about 300 to 400 m (1,000 to 1,300 ft) higher in elevation than the airport. Thus, the estimated wind power for Rock Springs is probably one to two classes lower than the wind power for exposed areas in that region.

8.3.1 Interannual Wind Power and Speed

Large interannual variations are apparent for many of the stations (Figure 8.10). The highest annual wind powers are as much as 2.5 times greater than the lowest annual wind powers at stations with the largest interannual variations, and about 1.5 times greater at stations with small interannual variations. However, the magnitude of the interannual variations may not be similar from different periods of record at a station. For example, at Casper, the period 1950 to 1958 had much larger interannual variations than the period 1965 to 1976.

The interannual curves also indicate years with relatively low or high wind energy. For example, Casper, Cheyenne, and Rock Springs all show relatively low wind energy for years 1969 and 1976. However, the interannual variations often do not coincide even at nearby stations, as shown in examples given in the discussions for Idaho and Montana.

8.3.2 Monthly Average Wind Power and Speed

Winter is the season of maximum wind power and speed at all stations, except for Moorcroft (Figure 8.11). Lowest mean wind speeds occur generally around July and August. The windiest winter months usually indicate three to four times the power of the lighter summer months (except for Moorcroft).

Because of the short period of record at Moorcroft and Sinclair, the monthly trends shown may deviate significantly from the long-term average. For example, at Moorcroft, the relatively high power in October is based on data from only 2 years and may not be representative of the long-term average. Other stations in that region that have summaries for 10 years or more (i.e., Sheridan, Wyoming and Rapid City, South Dakota) show higher mean wind speeds in spring than in autumn.

8.3.3 Diurnal Wind Speed by Season

All nine stations presented for Wyoming indicate maximum daily wind speeds during the afternoon for all seasons (Figure 8.12). Maximum wind speeds generally occur during the early afternoon (1200 to 1500 LST) in the winter and late afternoon (1500 to 1800 LST) in the summer. Wind speeds during the night show little variation but reach a minimum around 0600 to 0700 LST during the spring and summer at most of the stations.

The magnitude of the diurnal variation with season varies from station to station, but is usually greater in the summer and weaker in the winter. Except for mountain summits and ridge crests, these diurnal trends should be typical of most of Wyoming.

8.3.4. Directional Frequency and Average Speed

The prevailing strong winds are mostly from the west to southwest at stations throughout the southern Wyoming wind corridor (Figure 8.13). Nearby terrain influences these wind directions. For example, at the Casper Airport, strong south-southwest to southwest winds apparently result from the winds being channeled through gaps upwind (southwest) of Casper.

At Cheyenne, the prevailing strong winds are west-northwest to northwest. This is probably representative of areas in extreme southeastern Wyoming, east of the Laramie Mountains, as stations in extreme western Nebraska also indicate prevailing west-northwest to northwest winds. Throughout southern Wyoming, except for Laramie and Douglas, the frequency of winds from easterly directions is low. At Laramie, the valley is aligned south-southeast, parallel to the

Laramie and Medicine Bow Mountains and results in a secondary maximum directional frequency from the south-southeast. At Douglas, the prevailing east-southeast and northwest directions are approximately parallel to the orientation of the North Platte River plain and the Laramie Mountains, although strongest winds are west-southwest downslope from the Laramie Mountains.

8.3.5 Annual Average Wind Speed Frequency

Observer biases are readily apparent in the records for Douglas, Fort Bridger, Laramie, Moorcroft, Rawlins, and Sinclair, as peaks usually occur at 2, 5, and 8 m/s (5, 10, and 15 knots) (Figure 8.14). A high frequency of calms at Rawlins makes either the data or site exposure appear questionable. The frequency distribution at Sinclair is significantly different from that at Rawlins, even though the stations are only 10 km (6 mi) apart and are located at the same elevation in similar terrain. At Casper and Cheyenne, which have recent periods without any apparent observer bias, the Rayleigh distribution approximates the actual distribution reasonably well.

8.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 8.15 and 8.16. Abrupt changes in the slope of the duration curves correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

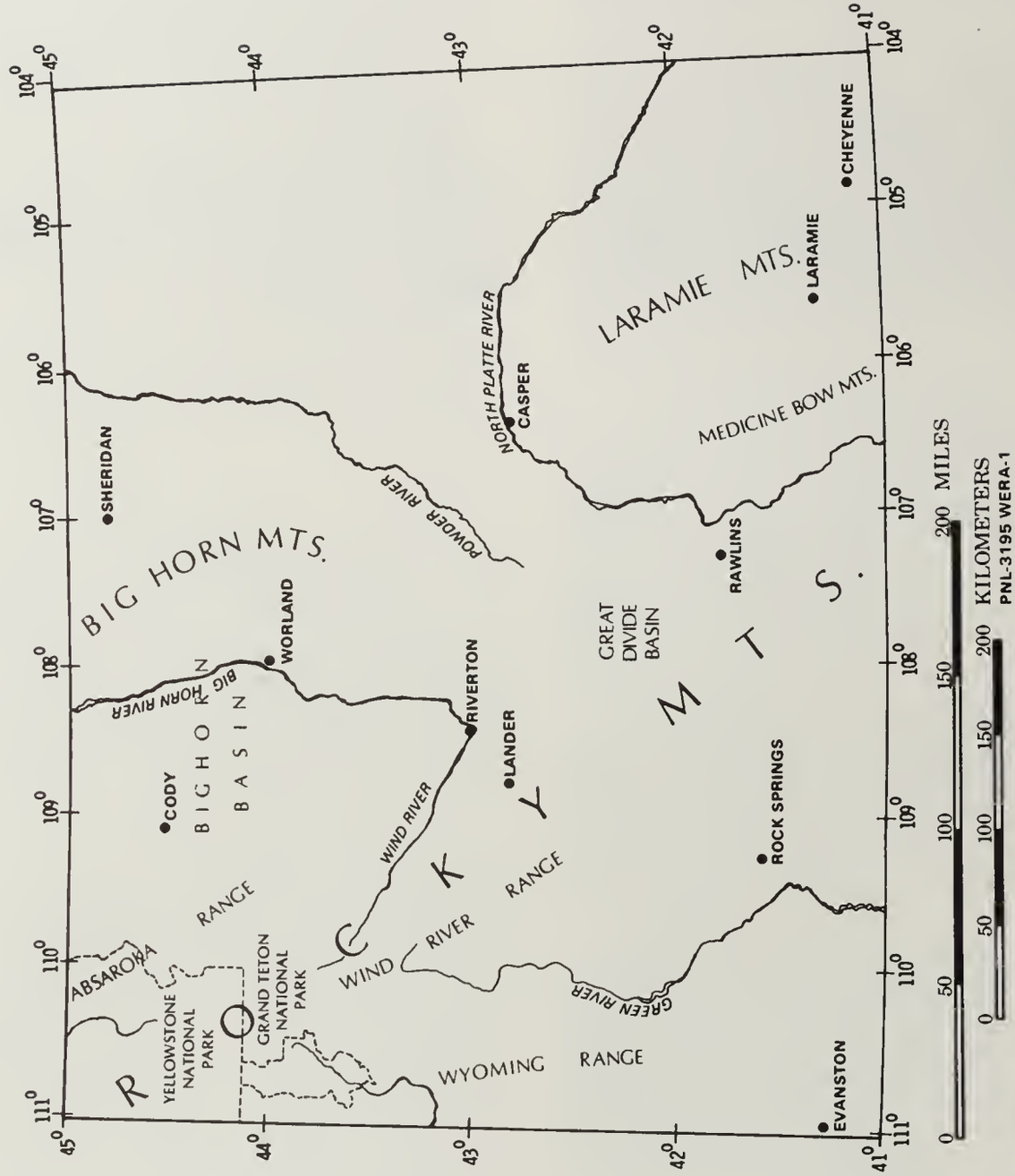


FIGURE 8.1. Geographic Map of Wyoming

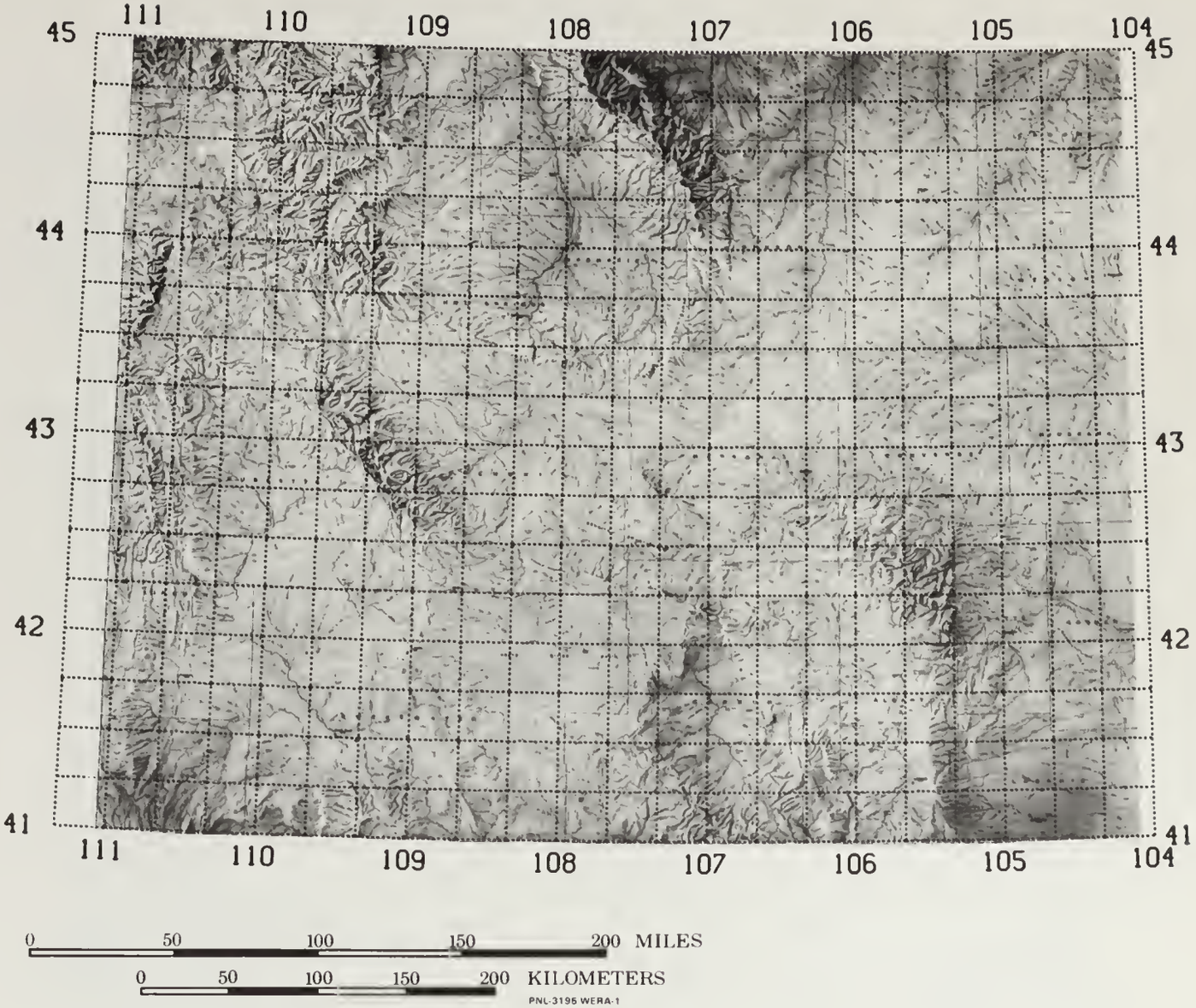


FIGURE 8.2. Topographic Map of Wyoming

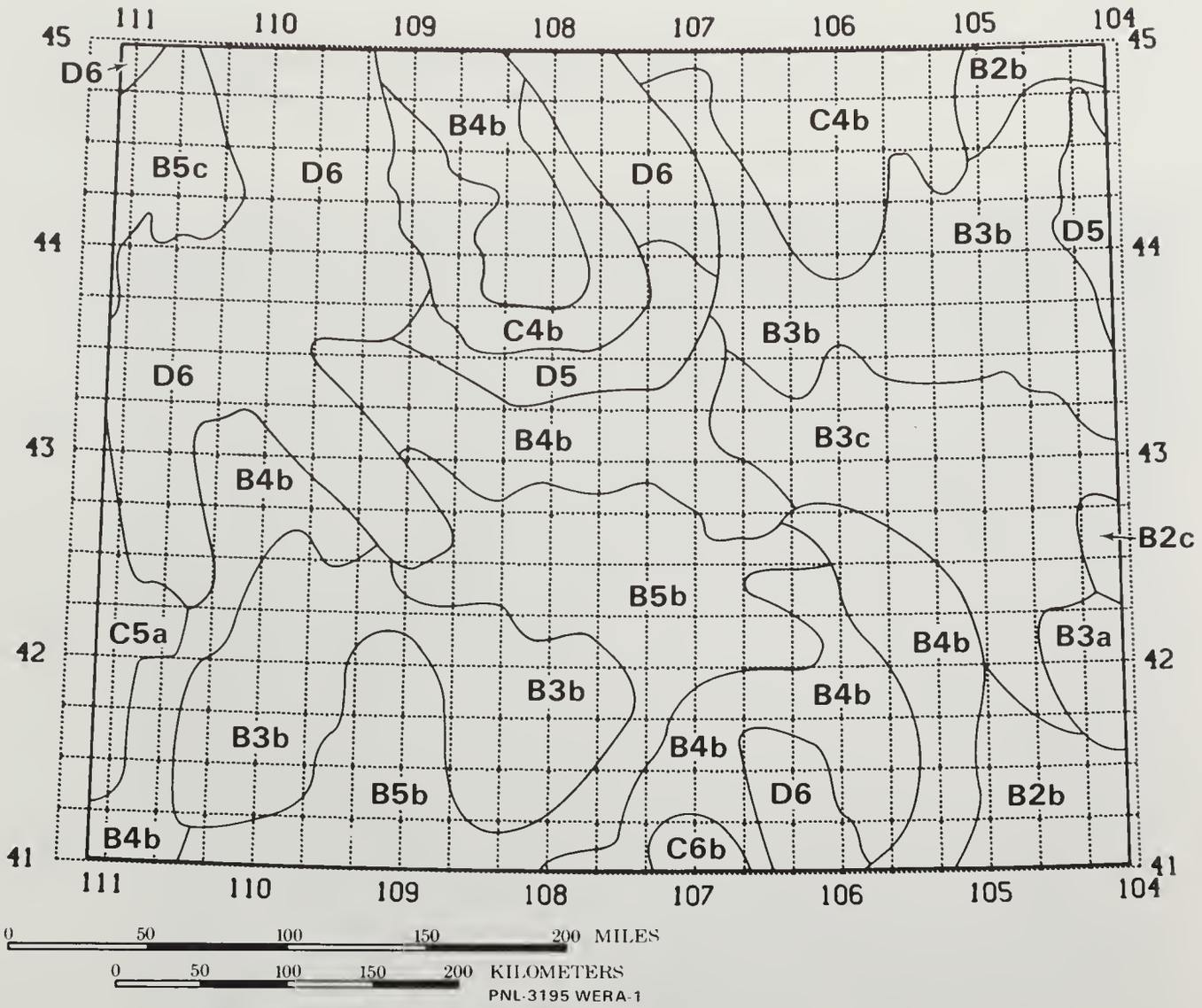


FIGURE 8.3. Land-Surface Form Map of Wyoming

LAND-SURFACE FORM LEGEND

PLAINS

A1	FLAT PLAINS
A2	SMOOTH PLAINS
B1	IRREGULAR PLAINS, SLIGHT RELIEF
B2	IRREGULAR PLAINS

PLAINS WITH HILLS OR MOUNTAINS

A,B3a,b	PLAINS WITH HILLS
B4,a,b	PLAINS WITH HIGH HILLS
B5a,b	PLAINS WITH LOW MOUNTAINS
B6a,b	PLAINS WITH HIGH MOUNTAINS

OPEN HILLS AND MOUNTAINS

C2	OPEN LOW HILLS
C3	OPEN HILLS
C4	OPEN HIGH HILLS
C5	OPEN LOW MOUNTAINS
C6	OPEN HIGH MOUNTAINS

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

TABLELANDS

B3c,d	TABLELANDS, MODERATE RELIEF
B4c,d	TABLELANDS, CONSIDERABLE RELIEF
B5c,d	TABLELANDS, HIGH RELIEF
B6c,d	TABLELANDS, VERY HIGH RELIEF

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

A	>80% OF AREA GENTLY SLOPING
B	50-80% OF AREA GENTLY SLOPING
C	20-50% OF AREA GENTLY SLOPING
D	<20% OF AREA GENTLY SLOPING

LOCAL RELIEF (2nd LETTER)

1	0 TO 30m (1 TO 100 ft)
2	30 TO 90m (100 TO 300 ft)
3	90 TO 150m (300 TO 500 ft)
4	150 TO 300m (500 TO 1000 ft)
5	300 TO 900m (1000 TO 3000 ft)
6	900 TO 1500m (3000 TO 5000 ft)

PROFILE TYPE (3rd LETTER)

a	>75% OF GENTLE SLOPE IS IN LOWLAND
b	50-75% OF GENTLE SLOPE IS IN LOWLAND
c	50-75% OF GENTLE SLOPE IS ON UPLAND
d	>75% OF GENTLE SLOPE IS ON UPLAND

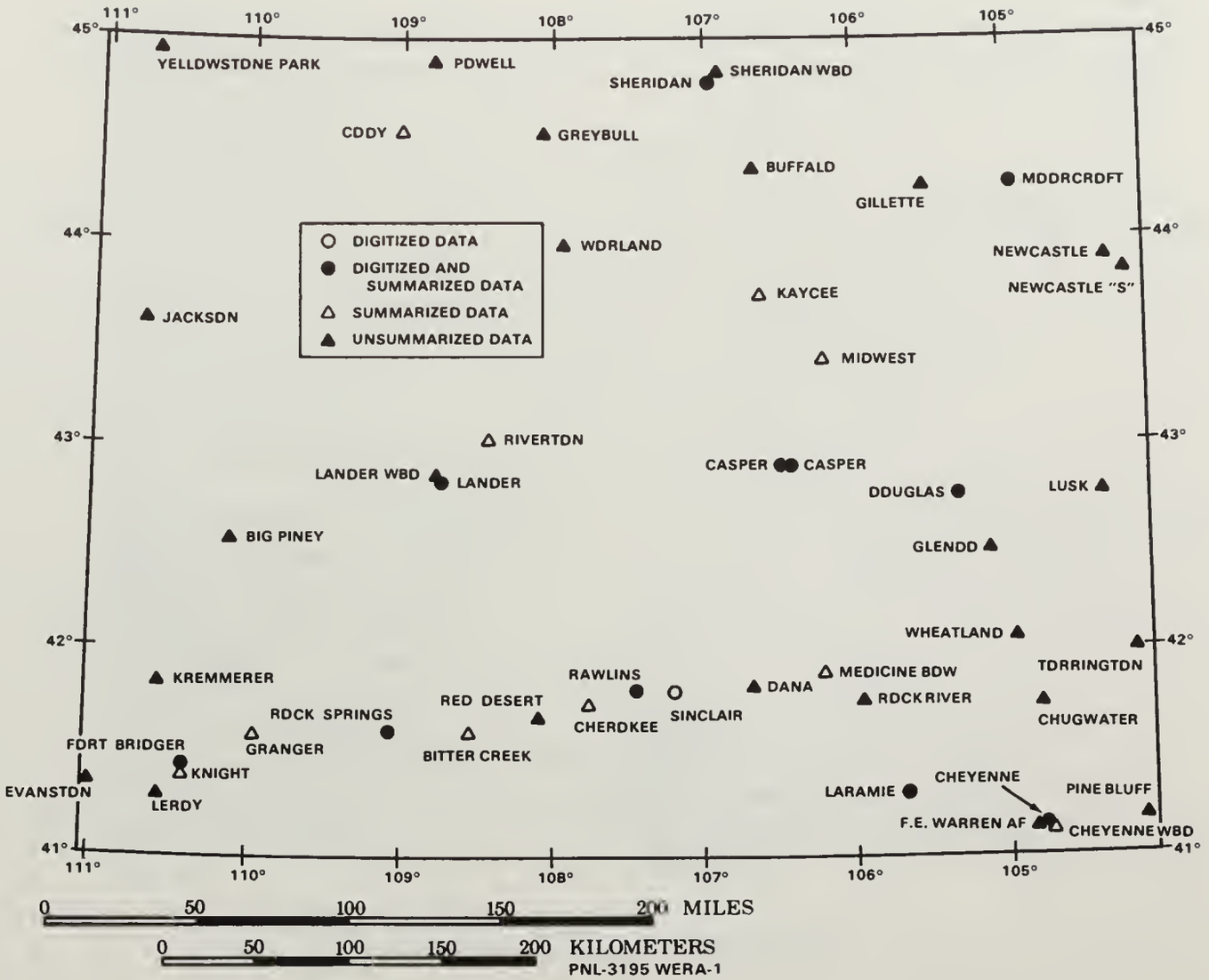


FIGURE 8.4. NCC Station Locations in Wyoming

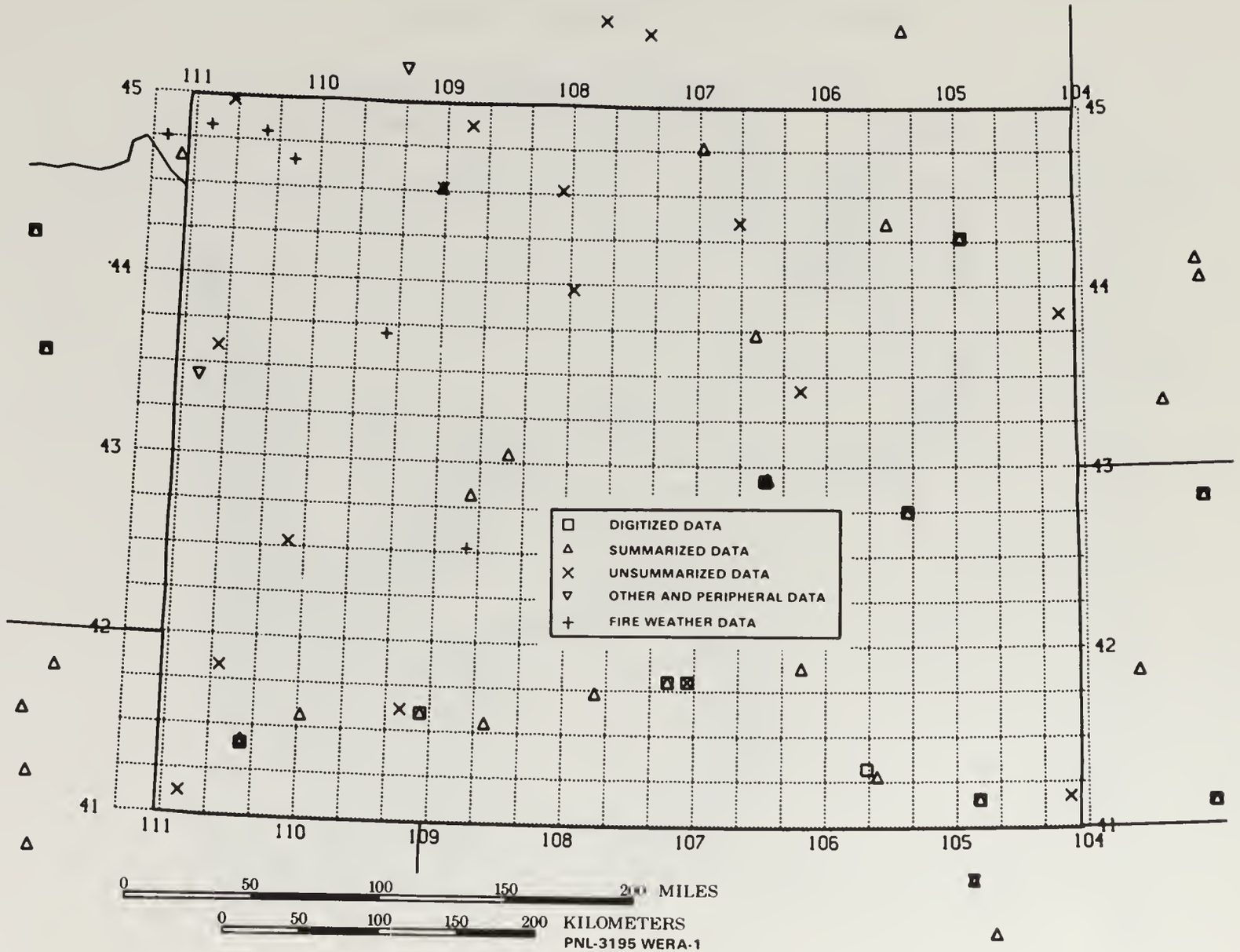


FIGURE 8.5. Locations of Stations Used in Wyoming Resource Assessment

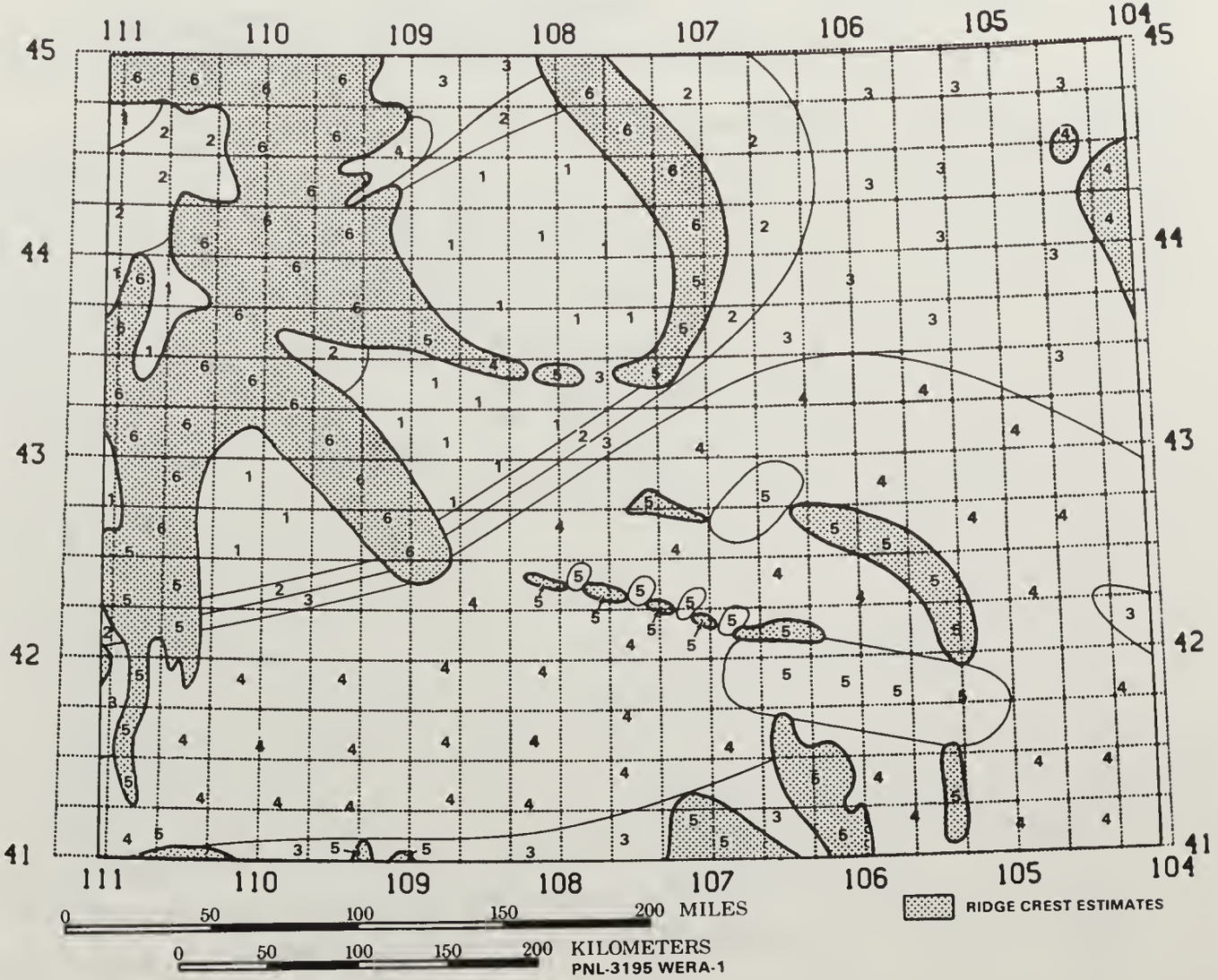


FIGURE 8.6. Wyoming Annual Average Wind Power

Classes of Wind Power Density at 10 m and 50 m[a]

Wind Power Class	10 m (33 ft) Wind Power Density, watts/m²	10 m (33 ft) Speed,[b] m/s (mph)	50 m (164 ft) Wind Power Density, watts/m²	50 m (164 ft) Speed,[b] m/s (mph)
	0	0	0	0
1	100	4.4 (9.8)	200	5.6 (12.5)
2	150	5.1 (11.5)	300	6.4 (14.3)
3	200	5.6 (12.5)	400	7.0 (15.7)
4	250	6.0 (13.4)	500	7.5 (16.8)
5	300	6.4 (14.3)	600	8.0 (17.9)
6	400	7.0 (15.7)	800	8.8 (19.7)
7	1000	9.4 (21.1)	2000	11.9 (26.6)

[a] Vertical extrapolation of wind speed based on the 1/7 power law.
[b] Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

TABLE 8.1. Areal Distribution (km^2) of Wind Power Classes in Wyoming

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	130,000	51.	250,000	100.
2	17,000	6.7	120,000	49.
3	30,000	12.	110,000	42.
4	66,000	26.	77,000	30.
5	8,500	3.4	11,000	4.4
6	2,500	0.98	2,700	1.1
7	200	0.08	200	0.08

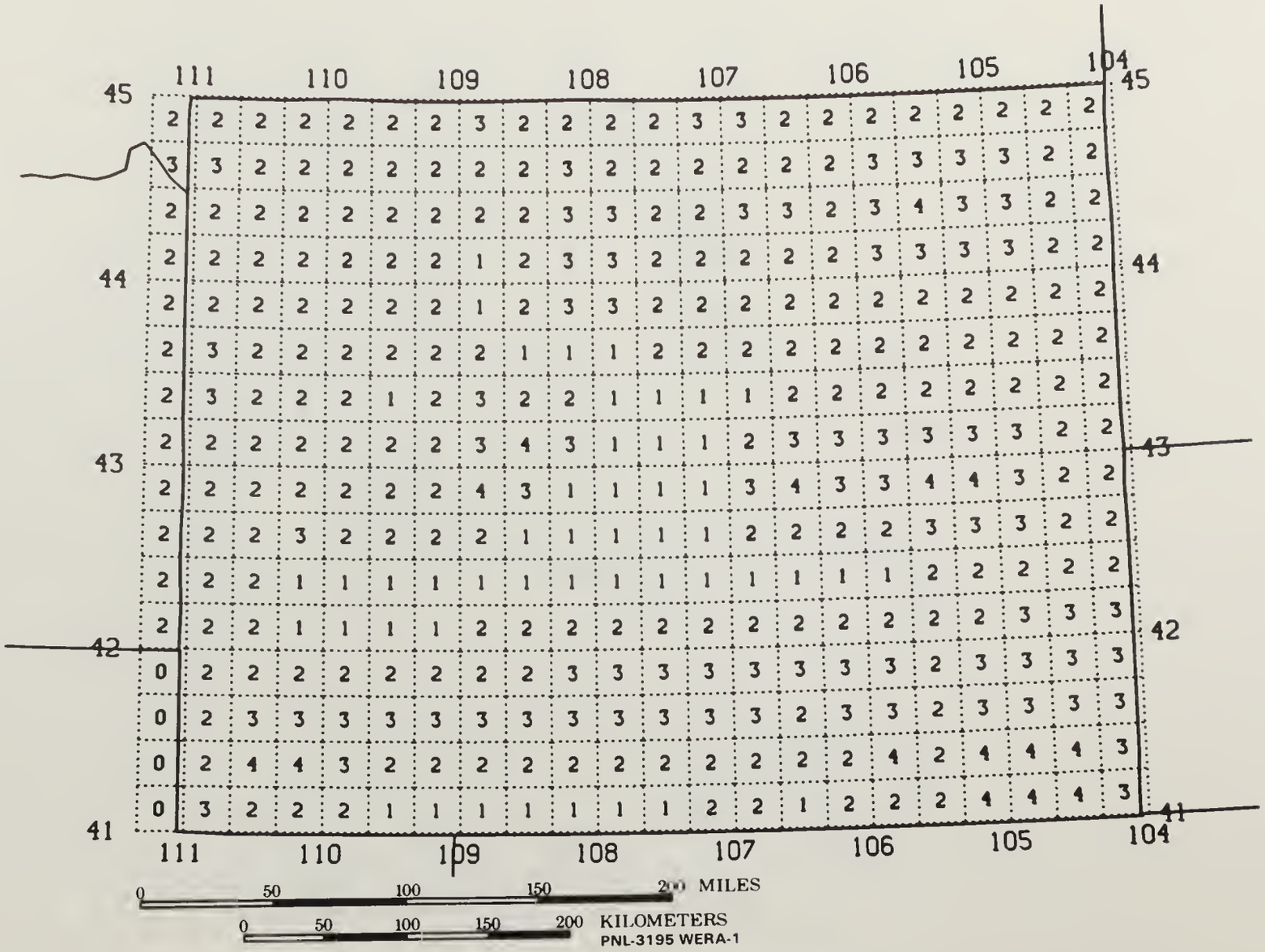


FIGURE 8.7. Certainty Rating of Wyoming Wind Resource

CERTAINTY RATING LEGEND

Rating	Definition
1	The lowest degree of certainty. A combination of the following conditions exists: 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	A low-intermediate degree of certainty. One of the following conditions exists: 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	A high-intermediate degree of certainty. One of the following conditions exists: 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.

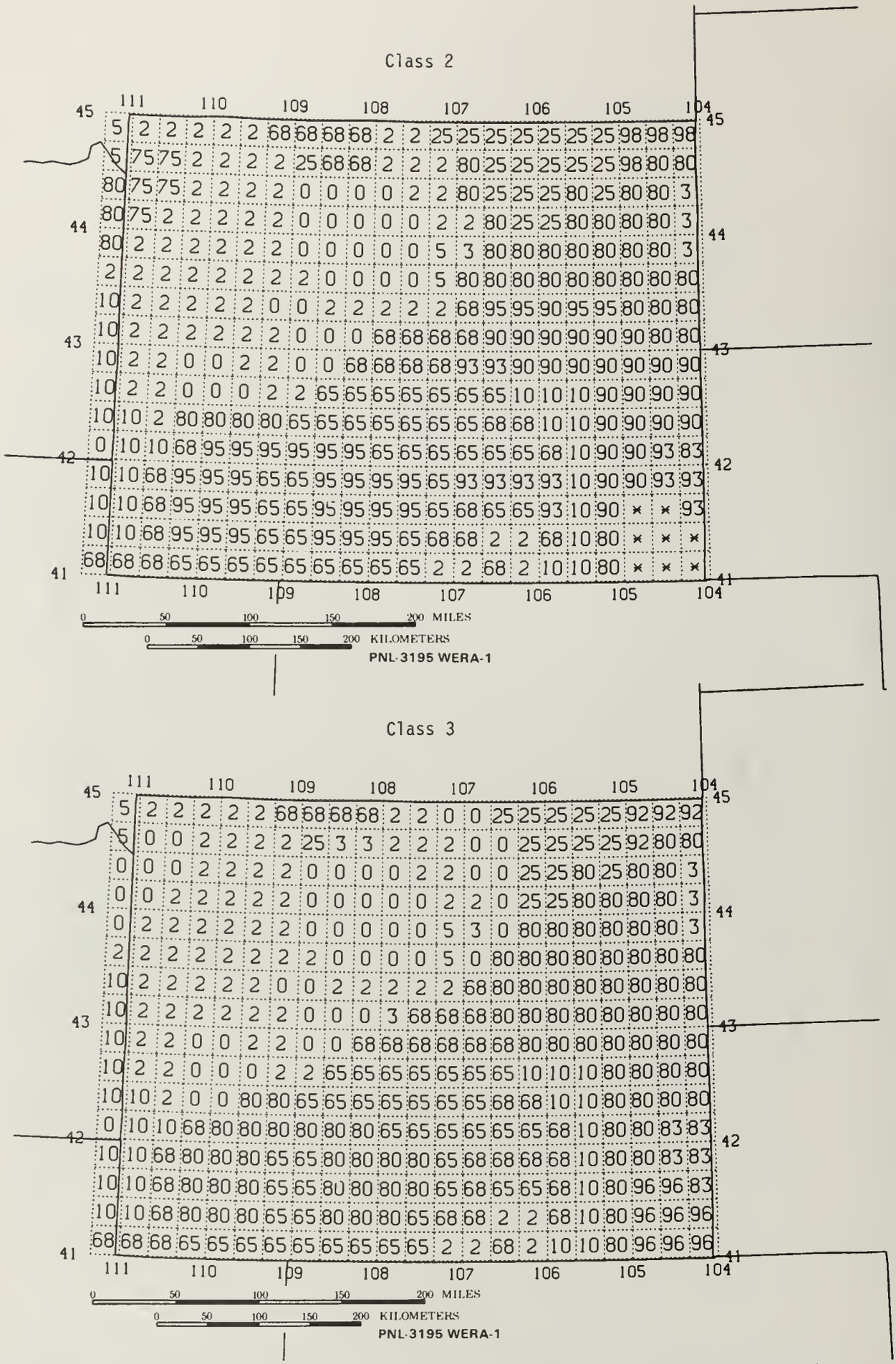
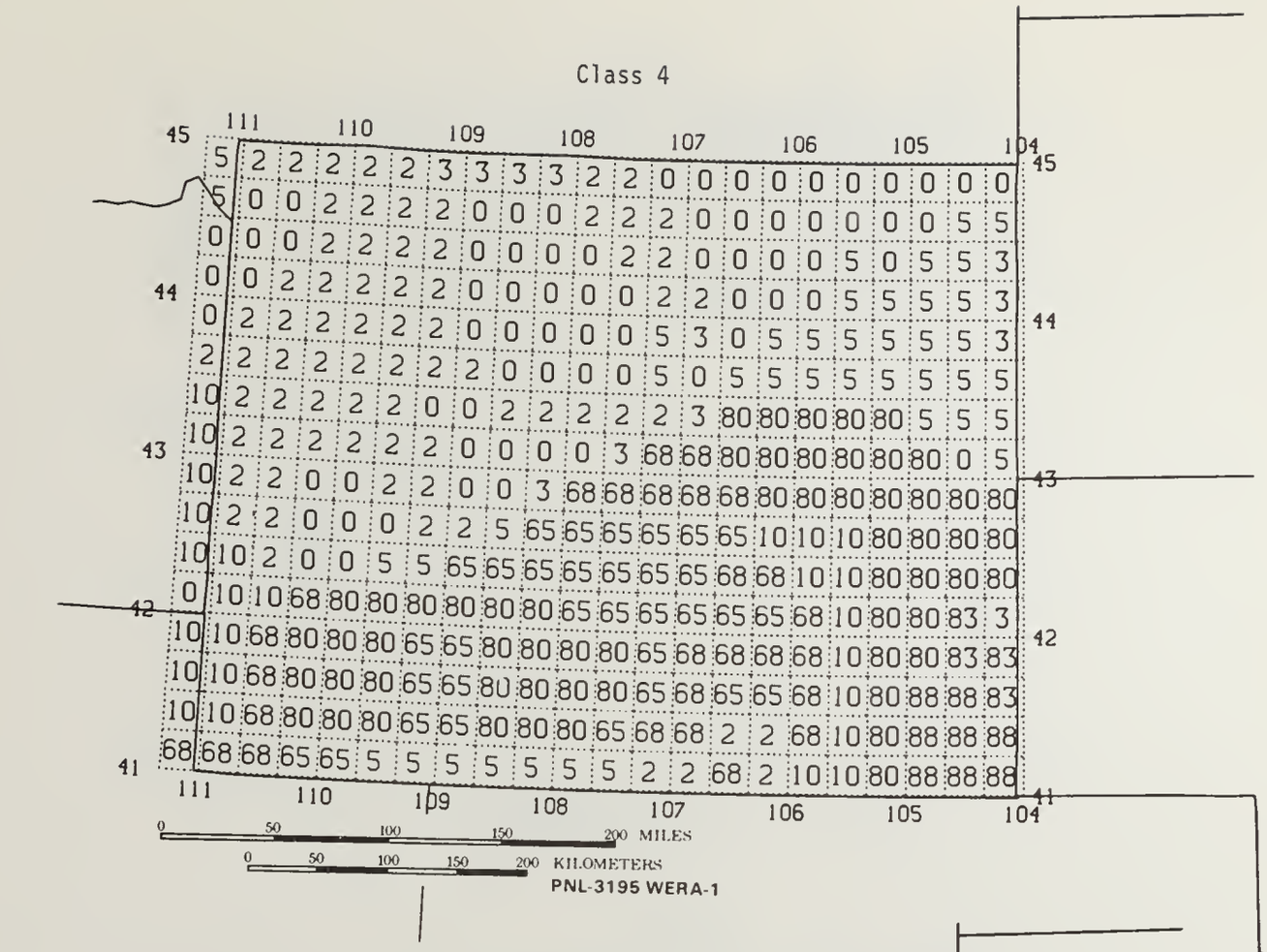


FIGURE 8.8. Areal Distribution of Wind Resource in Wyoming (Power Classes 2 and 3); Percent of Land Area With or Exceeding Power Class Shown. An asterisk denotes 100%.



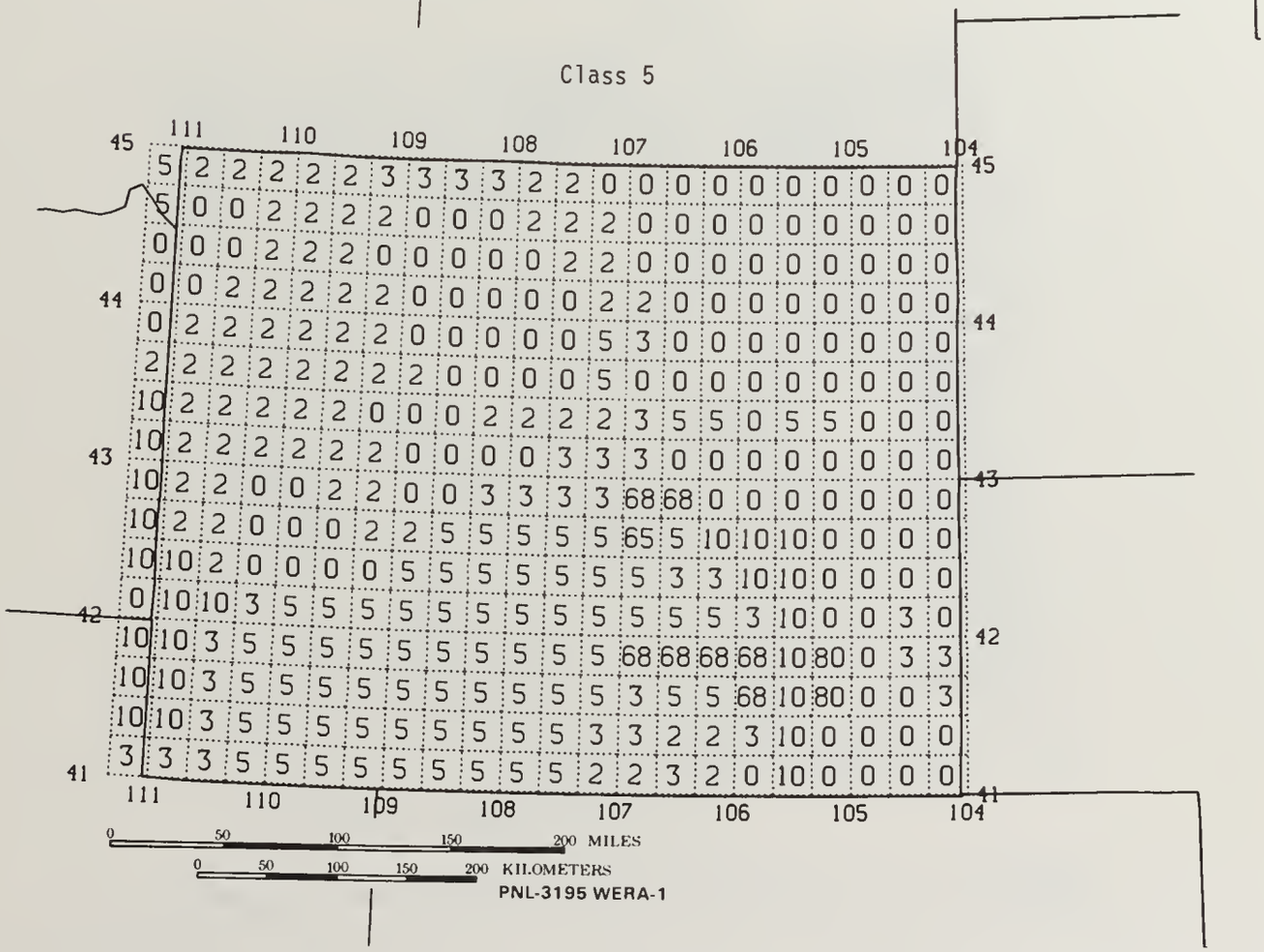
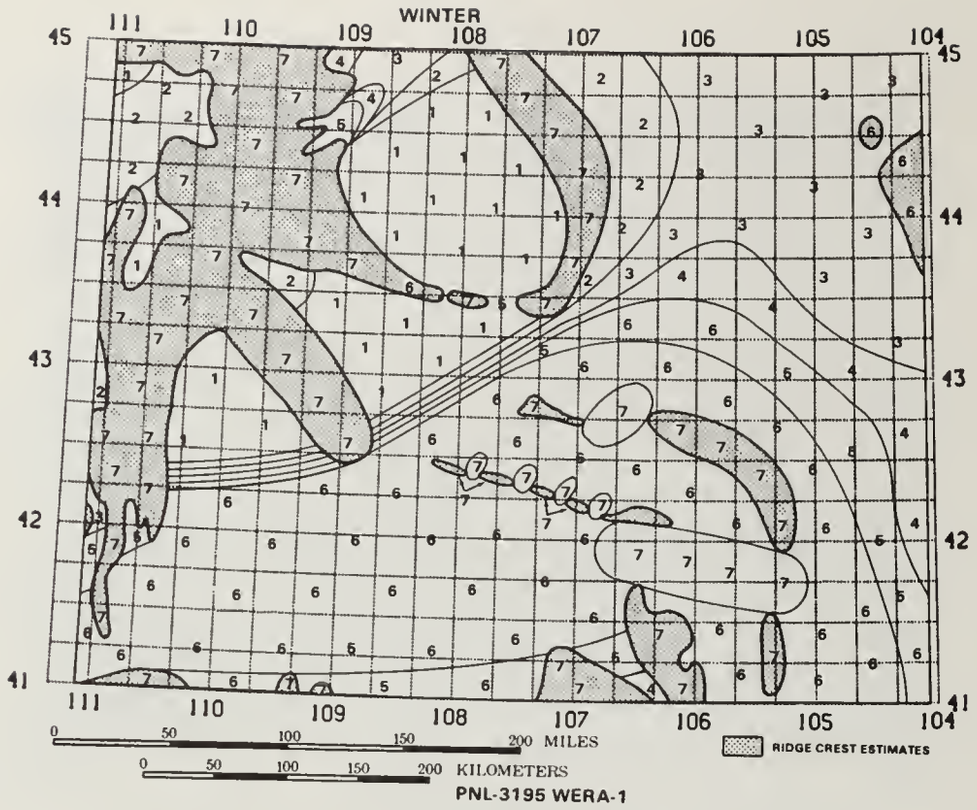


FIGURE 8.8 (Continued). Areal Distribution of Wind Resource in Wyoming (Power Classes 4 and 5); Percent of Land Area With or Exceeding Power Class Shown.



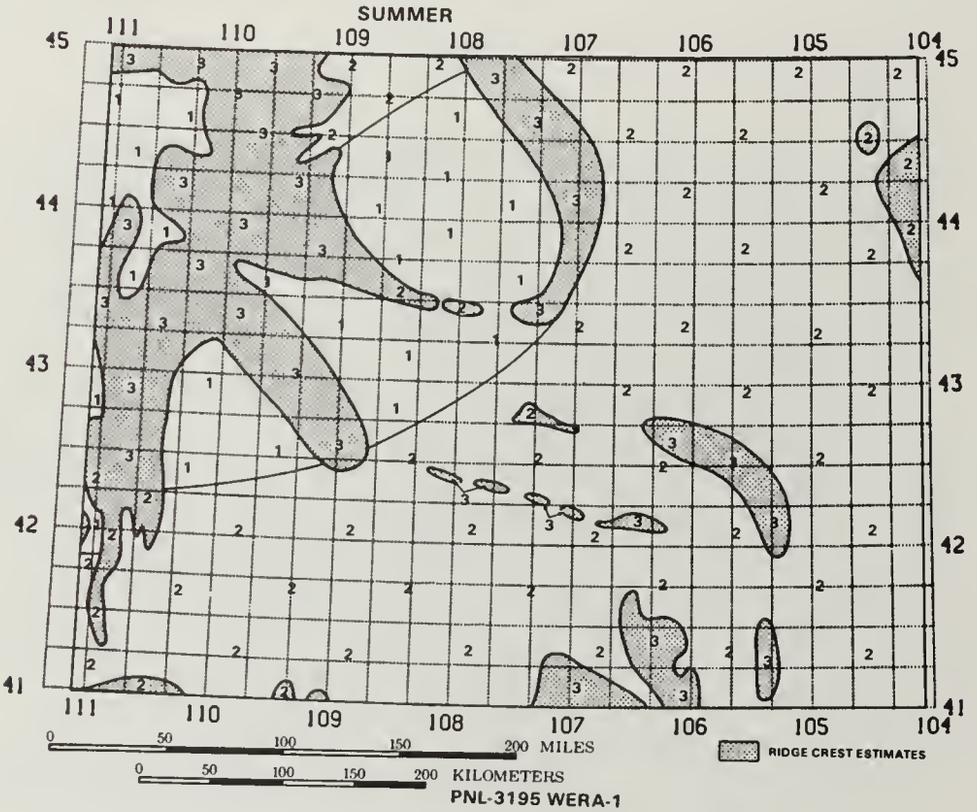
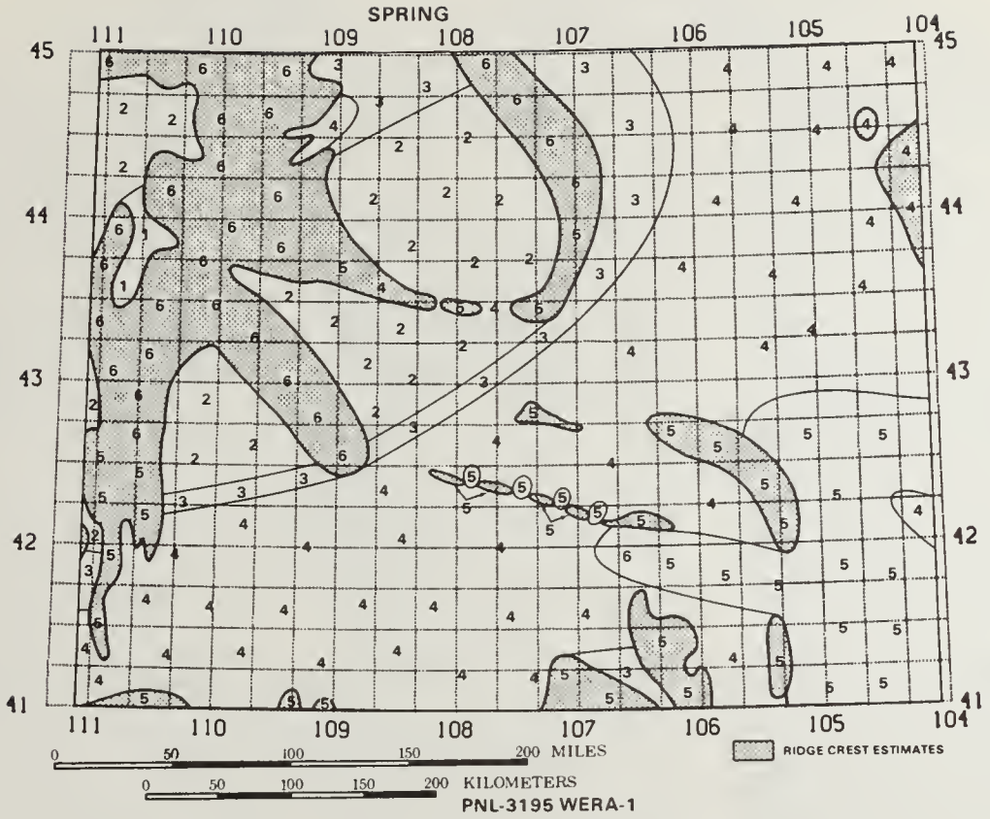


FIGURE 8.9. Seasonal Average Wind Power in Wyoming (Winter, Summer)



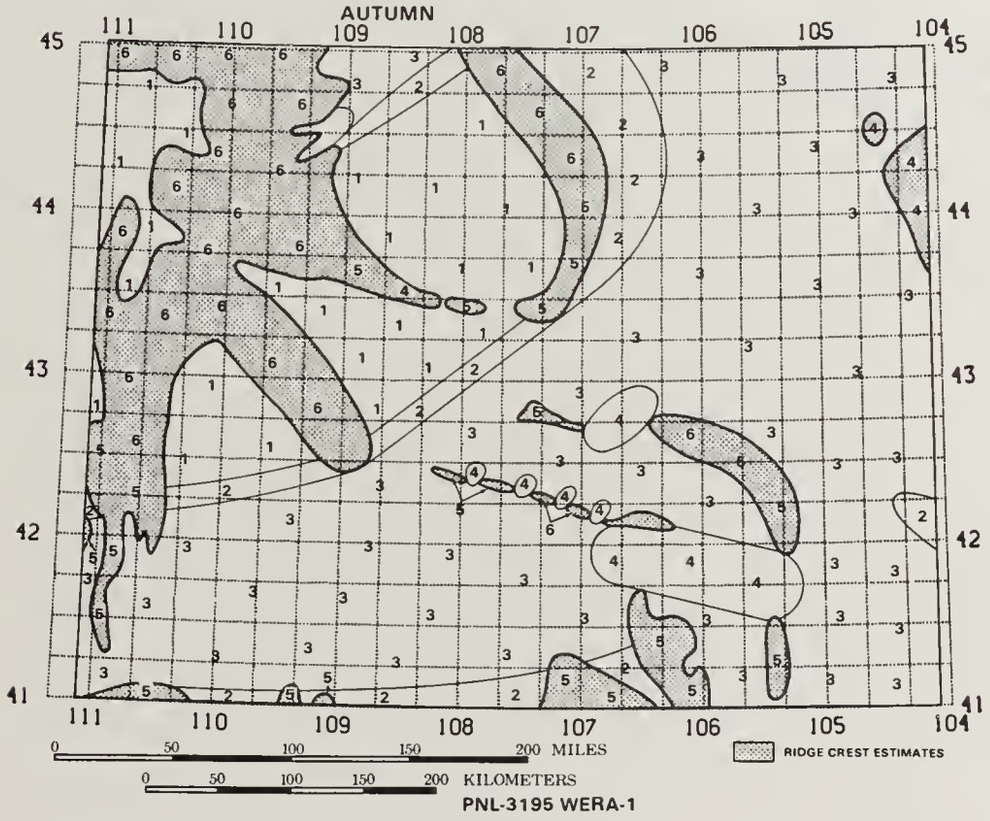


FIGURE 8.9 (Continued). Seasonal Average Wind Power in Wyoming (Spring, Autumn)

TABLE 8.2. Wyoming Stations with Graphs of the Wind Characteristics

Station	Station Name[a]	Latitude, Degrees North	Longitude, Degrees West	Elevation of Station, m	Period of Record, Month/Year	Anemometer Height, m	Annual Average Wind Speed, m/s			Annual Average Wind Power, watts/m²		
							At Anemometer Height, m	At 10 m	At 50 m	At Anemometer Height, m	At 10 m	At 50 m
Casper, Wyoming	Natrona County International Airport	42.92	106.47	1622	08/64-12/76	6.1	5.8	6.2	7.8	198	245	488
Cheyenne, Wyoming	Cheyenne Airport	41.15	104.82	1871	10/57-12/76	10.1	6.0	6.0	7.5	212	211	422
Douglas, Wyoming	Converse County Airport	42.75	105.37	1486	06/48-12/54	17.7	5.7	5.3	6.6	285	223	445
Ft. Bridger, Wyoming	Fort Bridger CAA	41.40	110.42	2136	06/48-12/54	18.3	6.6	6.1	7.6	313	242	482
Laramie, Wyoming	Laramie CAA	41.32	105.68	2216	01/48-12/54	19.5	6.3	5.7	7.2	255	192	382
Moorcroft, Wyoming	Moorcroft CAA	44.27	104.95	1300	01/50-07/52	9.8	4.3	4.3	5.4	128	129	258
Rawlins, Wyoming	Rawlins Airport	41.80	107.20	2055	01/55-12/64	8.5	5.2	5.3	6.7	188	201	401
Rock Springs, Wyoming	Rock Springs Airport	41.60	109.07	2056	07/60-12/76	6.1	4.9	5.3	6.6	135	167	333
Sinclair, Wyoming	Sinclair CAA	41.80	107.05	1999	01/48-02/51	8.8	6.6	6.7	8.5	402	424	845

[a]CAA-Civil Aeronautics Administration Facility.

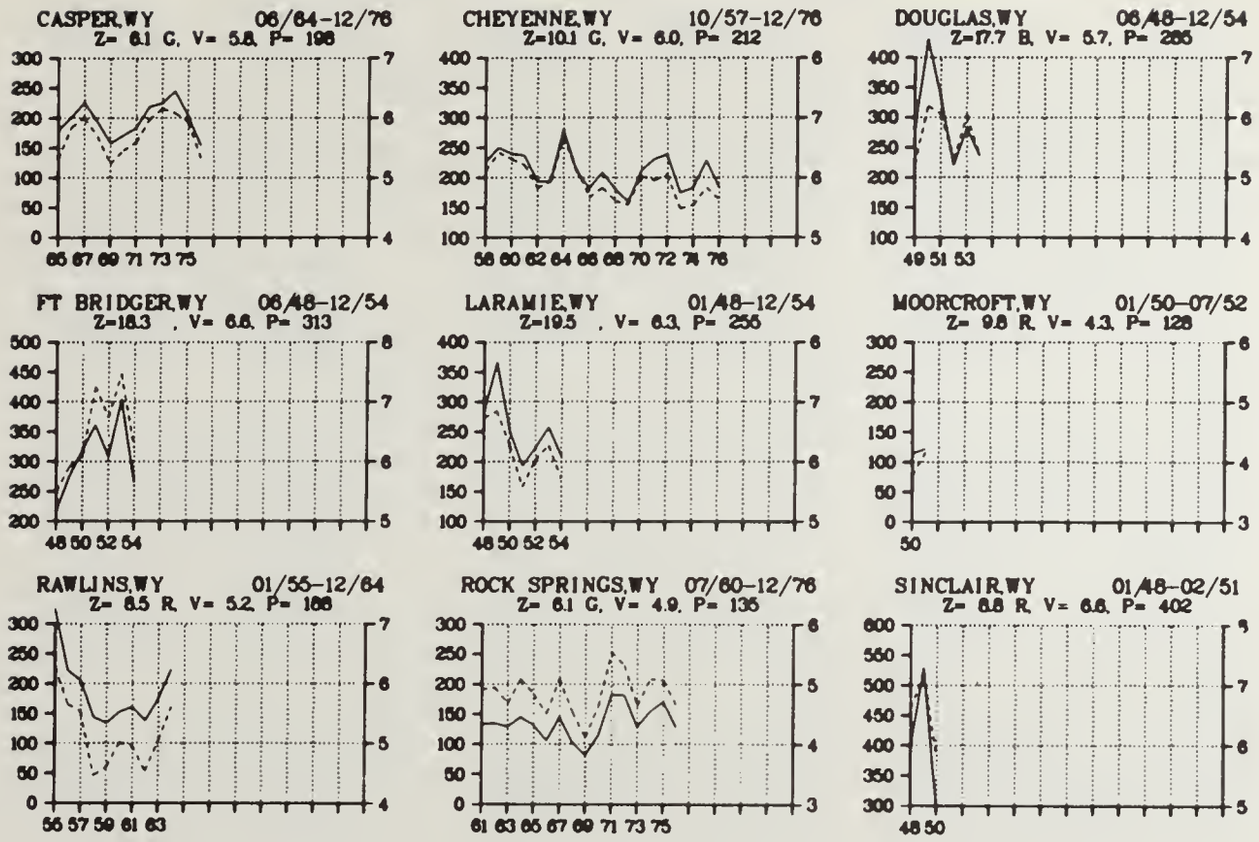


FIGURE 8.10. Interannual Wind Power and Speed for Wyoming

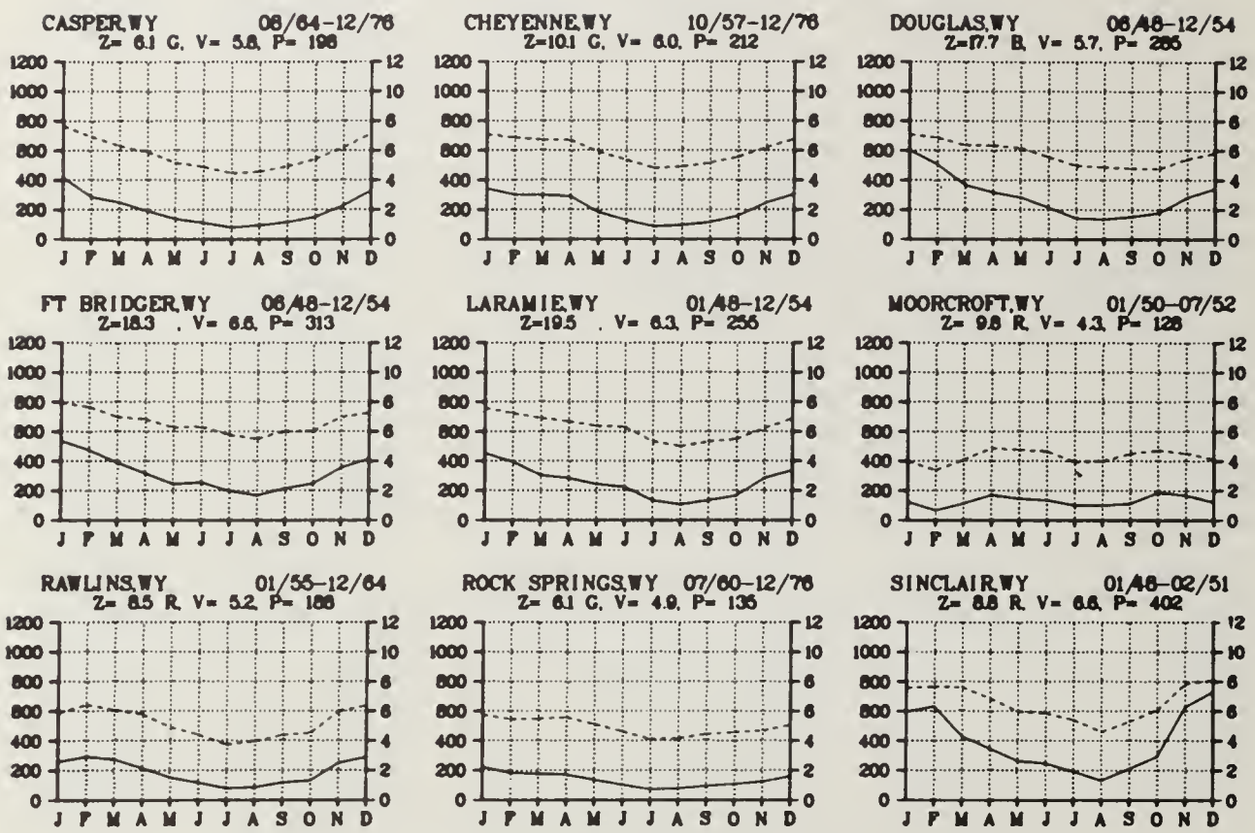


FIGURE 8.11. Monthly Average Wind Power and Speed for Wyoming

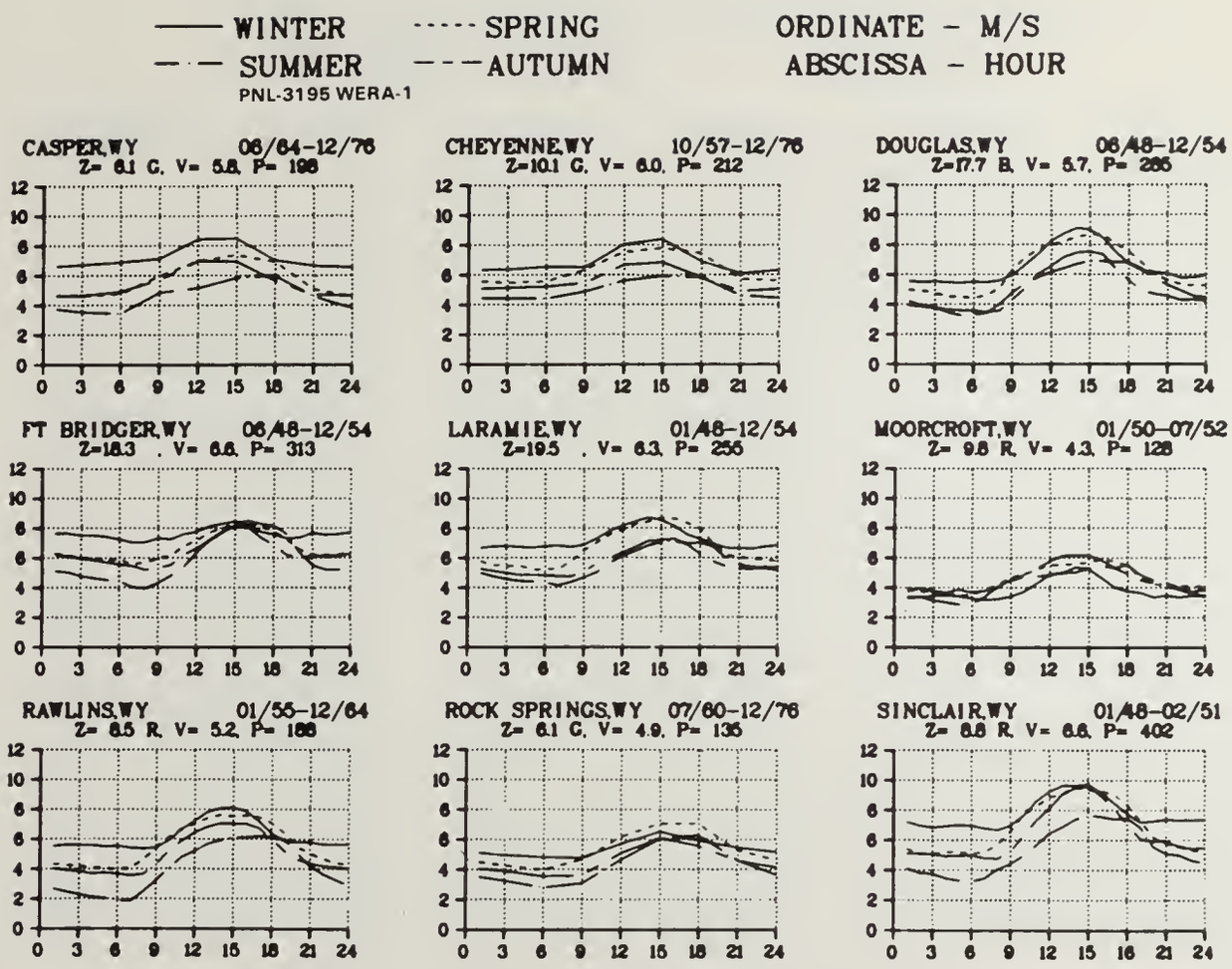


FIGURE 8.12. Diurnal Wind Speed by Season for Wyoming

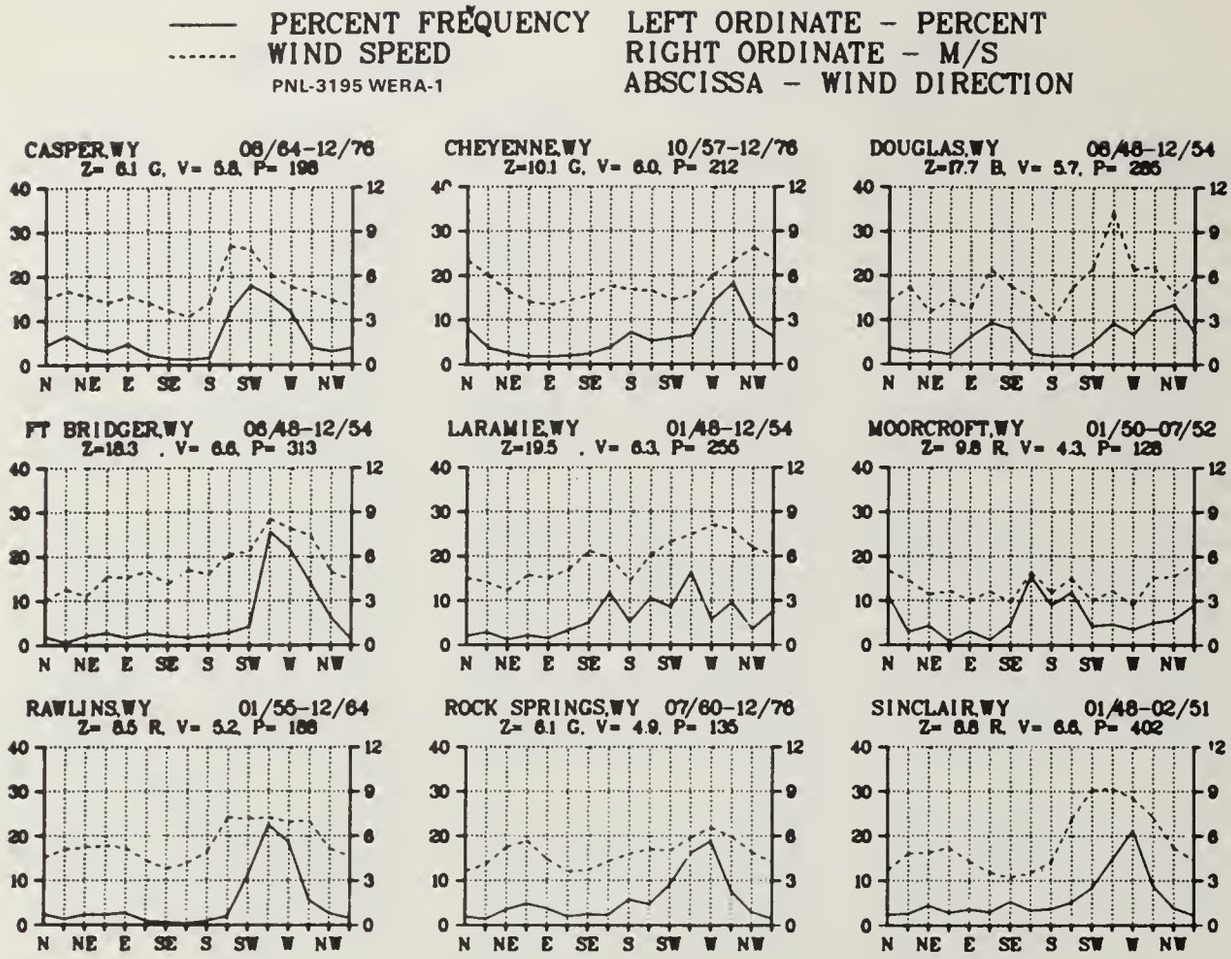


FIGURE 8.13. Directional Frequency and Average Speed for Wyoming

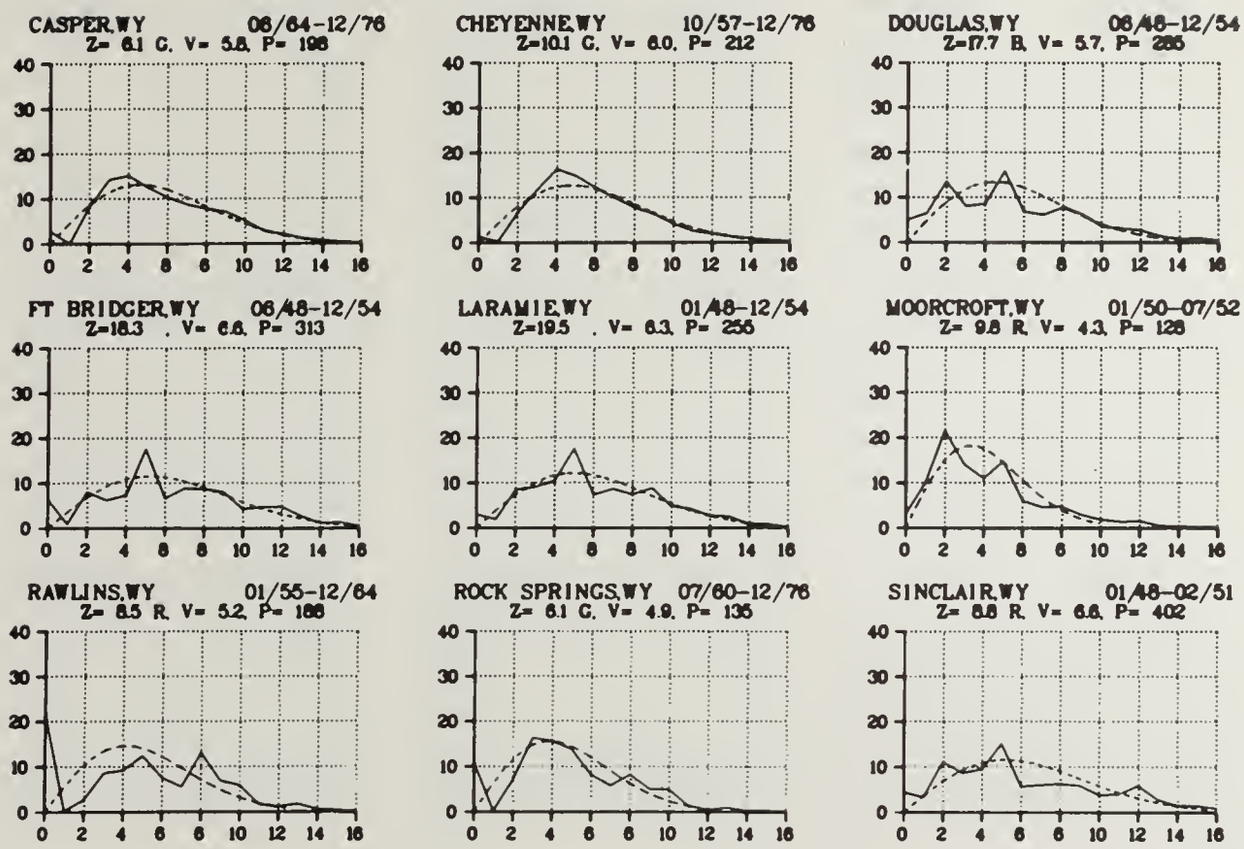


FIGURE 8.14. Annual Average Wind Speed Frequency for Wyoming

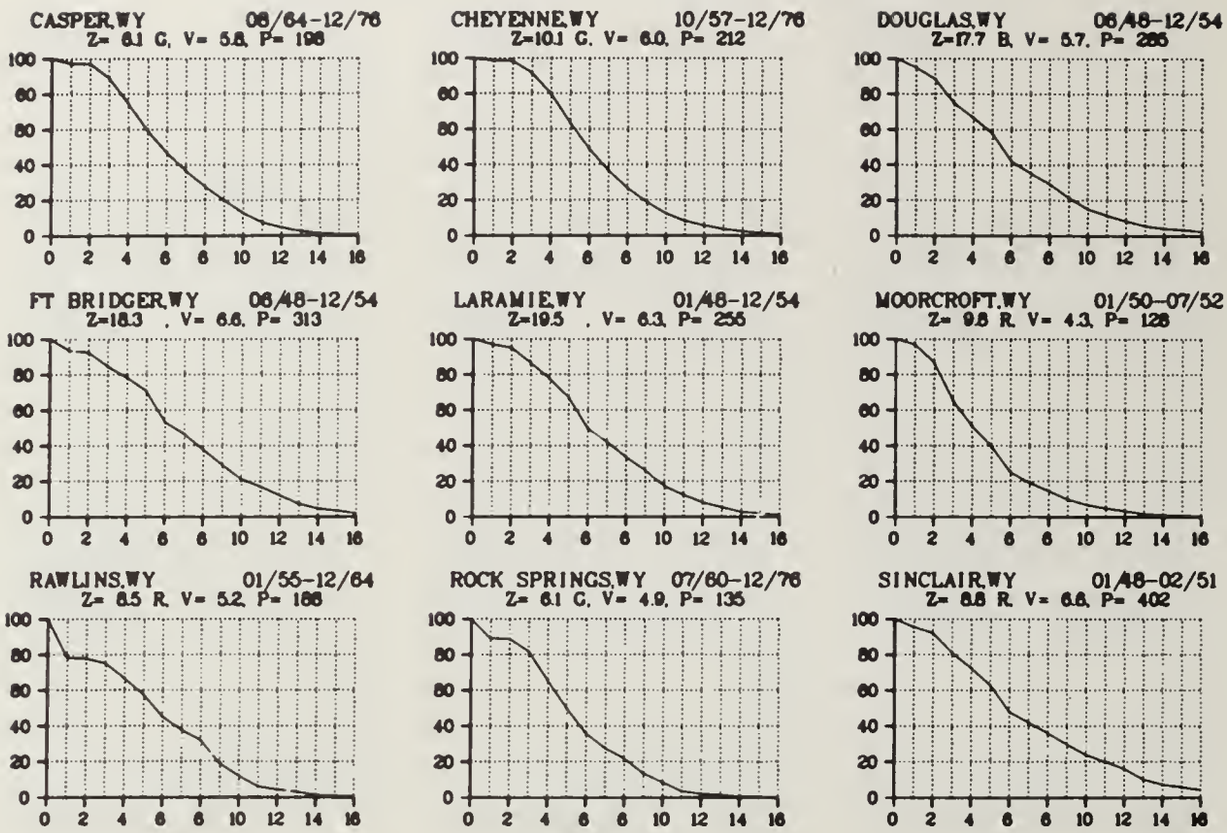


FIGURE 8.15. Annual Average Wind Speed Duration for Wyoming

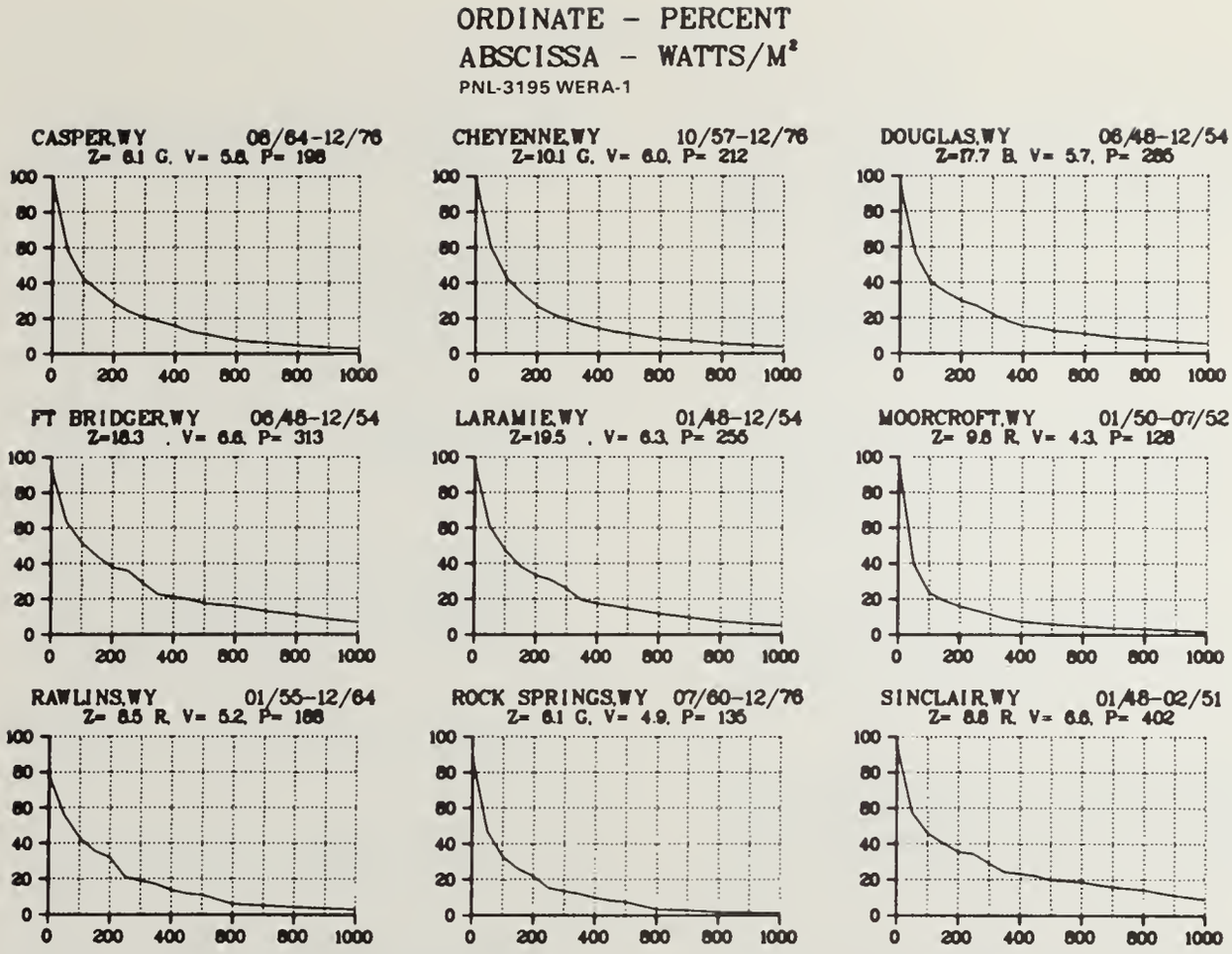


FIGURE 8.16. Annual Average Wind Power Duration for Wyoming

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